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FIRE DESIGN OF STEEL MEMBERS

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ABSTRACT:

The New Zealand Steel Code consists of few practical design tools other than finding the time and temperature that a simply supported steel member will fail. Many other design methods that consistently give accurate estimations of the behaviour of steel members have been published, and computer programmes developed to assist in the prediction of the temperature rise of steel when subjected to elevated temperatures environments.

This report describes the origins of the fire design methods used in the New Zealand Steel Code, NZS 3404:1997. The New Zealand Steel Code is reviewed and the design features are compared with the equivalent method found in the Eurocode, ENV 1993-1-2, which is the most advanced international steel fire code.

The methods of evaluating the temperature rise of protected and unprotected steel beams are also investigated. Results from the simple formulas included in the New Zealand Code, and those developed by the European Convention for Constructional Steelwork, ECCS, are compared with results from the time step 'spreadsheet' method and from the finite element computer programme, SAFIR, for the ISO 834 standard fire. The comparisons show that the spreadsheet method gives temperatures very close to the average temperatures calculated by SAFIR for all cross sections and protection layouts. The equations from ECCS and NZS 3404 give good results for unprotected steel, and for protected steel the ECCS equations appear to represent the thermal response of the steel quite accurately while the New Zealand Steel Code has no simple method of estimating the temperatures for protected steel.

The methods used for comparing the results with the ISO fire are then repeated with Eurocode Parametric fires, and with results from a real fire test.

Suggested improvements are made for the New Zealand Steel Code, to improve the concepts and information available to engineers designing for fire safety.

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1 INTRODUCTION:

1.1 OBJECTIVES:

The objectives of this study are:

1. To outline the design methods for fire engineering that are included in the fire section of the New Zealand Steel Code, NZS 3404:1997, determine their origin, and make comparisons of these with other equivalent codes from around the world.

2. To examine the validity and assumptions of the formulas given in the New Zealand Steel Code, and other international Steel Codes by comparing the formulas with simulations from computer programmes. The results from these methods will then be compared with results from tests completed on steel members where appropriate and available.

3. To make recommendations based on the results of this project, for changes to the New Zealand Steel Code, or alternatively to confirm the existing methods where appropriate.

1.2 PREVIOUS STUDIES:

Many other studies have been performed comparing the results from different methods of evaluating the temperature of steel members in elevated temperature environments. The purpose of these studies has varied from whether to establish a clear comparison of time equivalence methods; to comparing the different methods for cost saving reasons; or to further increase the confidence that designers have in the tools that are available to them.

Performance based design uses fire engineering principles to estimate and evaluate a structure's behaviour in a realistic design fire. The design is replacing prescriptive code in which the design of members is based on the results of tests that may not necessarily be relevant or appropriate to use for the structure being considered.

With the increase in performance based design being utilised around the world, there is a requirement for accurate estimations of member behaviour in fire so designs can be designed with confidence. Full scale tests are expensive, time consuming and can only be performed on a limited number of structural elements. Computer programmes and simple formulas, however, can be easily modified by changing a value applicable to the case, and once complicated methods are established, they can be reused by entering the appropriate information for the case.

Feeney, (1998), examined the design of a multistorey steel framed building without applying protective coatings, using performance based design. This report gives a background on the loadings for a building from a structural perspective and treats the fire loading in a similar way. The structure needs to be able to support a dead and live load under normal conditions and although the strength of the element decreases with increased temperature, so does the loading enforced on the element.

A detailed description is given to determine the maximum steel temperatures reached during a fire based on the ISO fire and a 'real' fire as determined from the Annex to Eurocode 1. An evaluation of structural performance is made based on the effects of increased temperature on the steel strength, load sharing between members of the structure and the design load likely to be present during a fire. A case study design of an apartment building in Auckland is worked through with the loads and temperatures estimated during a fire and the expected resulting strength calculated. A hotel building in Auckland is also similarly examined. This article shows that performance based design can eliminate the requirements of passive protection, reducing the cost of the building.

The suggestion in his report is to design for fire conditions so that protection is not required because the fire resistance of the unprotected steel member is sufficient in a fire. The conclusions however find the maximum likely temperature of the steel to be within 2 °C of the limiting temperature which is not very supportive evidence given the assumptions made and variability of steel beam sizes and properties when in place.

Spearpoint, (1998), compared the results from a finite element computer programme, THELMA, with results from a full size fire test at the test facility at Cardington, UK. The results showed THELMA gave reasonable predictions of the temperature profiles for unprotected steel members, but for protected steel the predictions did not compare as well with the experimental data. Results were compared for beams and columns between the results found from THELMA and the experimental data.

Bennetts, Proe and Thomas wrote a series of articles in 1986 on the calculation of the response of structural elements, on the thermal response, mechanical response and overall behaviour. The report (Bennett et al, 1986) on the thermal response includes an introduction giving background to the regulations of the existing codes at the time of when written. It also has a procedure for calculating the overall behaviour of a structural element in a fire based on thermal response of the element and strength of the element as a function of temperature. Methods for calculating the thermal response for protected and unprotected steel members are given. Various methods for calculating behaviour of protected members are given including methods with or without moisture and the CTICM method. These methods use simplified heat flow theory to predict the behaviour of steel members Regression analyses were also performed in the report to provide estimates and confidence limits of the temperature of the steel member. An application of the test results is included also, which compares theoretical calculations with experimental results.

Proe et al[1], (1986) is the second article of the series and outlines the mechanical response of steel including a brief overview of the purpose of the fire test – for calculating the thermal response of an element under fire loading and the strength of the element as a function of temperature of the element. The relationship between the tests to ECCS recommendations is commented on. A review of plastic analysis behaviour of steel members is included and methods to apply the basic principles to simply supported beams, built in beams, multi-span beams and struts. Plastic analysis under fire conditions is looked at with an outline of the behaviour of steel under elevated temperatures. Variation of steel strength with temperature is covered, when the member is treated as an isothermal member, and when variation within a member either along the member or within the depth of the member is considered. Mechanical properties of steel in a member such as expansion, modulus of elasticity and strength of struts is looked at. An analysis of the fire test behaviour includes correlations between the theoretical calculations and experimental data for beams with uniform temperature distribution, beams with a concrete slab and struts at uniform temperature.This paper uses methods to determine the load capacities of isolated beams and struts when subjected to a fire test. The plastic analysis method presented here assesses the member capacity under normal conditions and this analysis is extended.

Proe et al*[2] *(1986) is the third report which includes a summary of the thermal and mechanical response reports in this series. It also has methods to calculate overall response of the member, for beams and columns at uniform temperature and with temperature gradients within the depth of the member or along the member. The test data is correlated to the calculated results for results that both thermal and mechanical response can be calculated for. This includes beams with uniform temperatures and with temperature gradients and for columns with uniform temperature.

Although these articles are now dated and a lot of the results found have been further researched and different results found, this series was used extensively in the writing of the present New Zealand Steel Code.

In ***Kodur et al, (1999)***, there is a brief background to the design of steel structures and difference in performance based on analysing a single member compared with a complete structure. Background information about SAFIR is given and about the finite element method of analysis. The assumptions made when determining the element properties and magnitudes of displacements and rotation are included as is the procedure for analysis of the behaviour of a structure. A case study analysis of three members is worked through withfourdifferent fire protection options on the elements.

An ISO 834 fire curve is used to model the fire and output was set to come out at 2 minute increments, with the analysis continuing until failure occurs in one of the members. The results of the four tests are given with comparisons between them. The paper concludes that SAFIR can be used to perform thermal and structural analysis, and that SAFIR can be used to study the overall behaviour of structures under fire conditions because it is of finite element formulation.

It also concludes that there is an improvement in the fire resistance performance of a beam when acting as a part of a structure than when acting alone as a single member, and that the effect of slab-beam interaction has to be accounted for in the analysis to assess the realistic fire resistance of a steel frame.

Milke, (1999) describes the work that is being done by a joint ASCE and SFPE committee working towards a standard for performance based fire resistance analyses. This standard will include: descriptions of characteristics of exposure from a design fire; material properties at elevated temperatures and heat transfer and structural analysis methods. This paper therefore includes a background of the requirements that structural members must uphold during a fire. The fire exposure to the member needs to be characterised and the heat transfer coefficients and temperature needs to be specified for different scenarios. The properties of steel at elevated temperatures change from that of ambient conditions and this affects the thermal response, and structural analysis. Included in this paper is an overview of the heat transfer and structural analysis methods including moment analyses for beams and slabs and stability analyses for columns and walls.

Gamble, (1989) wrote an early paper giving the background and theory to the spreadsheet method of predicting the temperature of protected steel beams. The paper includes three worked examples with different types of protection and the response that the steel member should have, with all working to make a clear guide. The theory to the formation of the equations used is provided, as are explanations with examples.

Franssen et al, (1994), wrote a report comparing 5 different computer programmes, analysing three structures under different temperature profiles, with 8 comparisons being made in total. The computer programmes examined are CEFICOSS, DIANA, LENAS, SAFIR and SISMEF. The horizontal displacement is given graphically for each test, and maximum values summarised in a table. The maximum difference in ultimate values between any two programmes was found to be 6%, although DIANA had a substantial deviation from the others for heating with an axially loaded column. Some explanations are offered for the difference between DIANA and the other programmes, but no firm conclusion as to the reason is given. The programmes are concluded to be very similar for bending members, and for members with axial loads, the ultimate loads can be found with some confidence, however the history of the member can not be accurately given.

Gilvery and Dexter, (1997), prepared a report for and funded by NIST to determine the possibility of using a computer programme to estimate or evaluate fire resistance times and load capacity of structures subjective to fire, instead of conducting full scale furnace tests. The purpose behind the project was to establish if a computer could accurately model the behaviour of a member in a fire, and therefore save a lot of money. A range of possible approaches were evaluated from simple calculations to sophisticated numerical simulations. Simple calculations were found to be good for members with a uniform temperature distribution, but for members with non uniform temperature distributions, computer programmes were better. The paper reports that one of the best computer programmes is SAFIR in terms of its 'user friendliness' and accuracy. The use of SAFIR is shown by modelling complex structural elements, and evaluating special situations such as partial fire exposure and exposure of a continuous frame to fire in one bay. It is concluded that SAFIR is a very useful tool that could be used as an alternative to furnace testing.

A University of Canterbury research report by ***Wong, (1999),*** on the reliability of Structural Fire Design used the computer package @RISK to calculate the probability of failure of structural steel elements designed for fire conditions. The @RISK programme uses the standard deviation of the factors involved in the design of a steel member and runs simulations to find the probability of failure of the member with all factors considered. The results show the shortcomings in design and an option to enhance the performance based design of structures.

1.3 SCOPE OF THIS REPORT:

This report is concerned with the design of single simply supported beams and columns that will fail when the load capacity is reached and exceeded at one critical point of the span, when a plastic hinge will develop and cause failure of the steel member. The results found in this report do not apply to complex structural arrangements such as frames and built in members as the effects from moment distribution between individual members means that multiple plastic hinges must form before failure occurs.

Results from experimental tests show that more complex structural arrangements often have more fire resistance than single members. Results from series of tests from Cardington and articles such as O'Connor and Martin, (1998) who reported the results of tests studied by British Steel indicate that unprotected steel frames behave significantly better than indicated in single member tests.

1.4 NZS 3404:PART 1:1997 SECTION 11:

The New Zealand Steel code, (SNZ, 1997) includes a section devoted to the fire safety of essential steel elements of a structure. The section includes formulas to estimate the maximum temperature that an element can reach before it will no longer be able to carry the design fire load and therefore fail, and the time until this temperature is reached. These formulas are based on the member ends being simply supported, so no redistribution of loads is allowed for. This gives a conservative design of elements as a lower temperature of the element will result in failure than if the element was 'built in' to a frame with axial restraint and moment redistribution possible.

Other design tools for fire included in the section are formulas that estimate the variation in mechanical properties of steel with temperature. These are the Yield Stress and Modulus of Elasticity of steel, whose variation with temperature dictates the strength of the steel at a particular temperature

The time until the limiting temperature is reached, the variation of temperature across the cross section and the rate at which the temperature increases, depends on the element cross section, the perimeter exposed to the fire and the protection applied to the member. This is accounted for in the code equations by a ratio of the heated perimeter of the member to the cross sectional area of the steel member, known as the section factor, or H_p/A (m^{-1}). This value is the inverse of the average thickness of the steel member so gives an indication to the rate of temperature rise.

In NZS 3404:1997, there are formulas provided for three and four sided exposure to the fire for unprotected members. For protected members the temperature of the element with time is based on a single experimental test exposed to a standard fire, with conditions specified to ensure that the results of the test will be equal or more conservative than what will occur in the element being examined.

If results of a series of tests are available, a regression analysis method is also included to allow an accurate estimate of the temperature of the element from these tests. The limitations are specified in this section and a window of results is also present which all interpolations from the regression analysis must fit into.

Determination of the period of structural adequacy is also based on a single test, provided the conditions the test was performed under are similar to that of the element being considered. For three-sided fire exposure there are limitations on the density of the concrete and the effective thickness of the slab.

Special considerations for sections of members such as connections with protected and unprotected members, and three-sided exposure with penetrations into concrete are outlined in this section of the New Zealand Steel code also.

1.5 OTHER STEEL CODES

1.5.1 BS 5950:Part 8:1990

The British Steel Code, (BSI, 1990) contains methods similar to those stated for NZS 3404 above.

It outlines the behaviour of steel in fire giving constant values for the thermal and mechanical properties of steel, and lists the reduction of strength in a table with different values for different levels of strain. The fire limit states are then presented which includes the safety factors used in design of steel members at elevated temperatures.

The methods for evaluating the fire resistance of unprotected and protected steel members are outlined, including using results from experimental tests. The calculation methods are limited to using reduction factors in general design equations, or finding limiting temperatures from tables.

1.5.2 AS 4100:1990

The Australian Steel Code is exactly the same as the New Zealand Steel Code except for a few minor alterations. These differences are in the upper temperature limitation for the time at which the limiting temperature is reached for unprotected steel, and the use of the exposed surface area to mass ratio (k_{sm}) instead of the section factor as used in NZS 3404.

1.5.3 ENV 1993-1-2

Eurocode 3 is a large document containing much information concerning the fire design of steel structures and is covered in more depth in Sections 3 and 7. It contains three main methods of evaluating the design resistance of a steel structure or member. These are the global structural analysis, which is the analysis of the whole structure; analysis of portions of the structure, which is the analysis of a section of the structure; or member analysis, which is the response of a single member to the elevated temperatures.

The thermal and of steel are given in a detailed equation form, or a suggested constant value. The mechanical properties of steel are given in tabular form.

Design of members is given in detail, but is the same as cold design but with reduction factors accounting for the strength loss at elevated temperatures. The temperature of unprotected and protected steel is given in a lumped mass time step form, with the increase in temperature being based on the energy transferred to the member during a short time period.

There is a provision allowing for the use of advanced calculation methods such as finite computer programmes to estimate the behaviour of a steel structure in a fire.

1.6 BACKGROUND INFORMATION:

1.6.1 Forms of Heat Transfer:

Finite Element computer software, such as SAFIR use three forms of heat transfer to evaluate the temperature of the steel member. These heat transfer forms are also accounted for by the equations used by the spreadsheet method.

Radiation:

Radiation is the strongest form of heat transfer as the energy transferred between two bodies is related to the fourth power of the temperature. Radiation transfers energy via electromagnetic waves and these will be intercepted by any object which can 'see' the emitter. Unlike convection and conduction, heat can travel by radiation through a vacuum (a space with no particles), although on earth there is always a medium, air, which radiation must travel through (Tucker, 1999).

The general formula for radiation between an emitting surface and a receiving surface is:

$$q = \varphi\varepsilon\sigma\left(T_e^{\,4} - T_r^{\,4}\right) \qquad 1.1$$

Where T_e is the temperature of the emitting surface (fire temperature), and T_r is the temperature of the receiving surface (steel element temperature).

When using this formula in the spreadsheet analysis, the emissivity, ε, is assumed to be 0.5, which is the default setting in the SAFIR programme. The temperatures are expressed from the absolute temperature scale (Kelvin), and the Stefan-Boltzmann constant, σ, has a value of 5.67×10^{-8} kW/m^2 K^4.

The configuration factor, φ, is an estimate of the fraction of the area that the emitter occupies of all that the receiver can 'see'. This has been assumed to have a value of unity during this project.

Convection:

Convection arises from the mixture of fluids, either liquid or gaseous that are at significantly different temperatures to result in different densities. Heat transfer takes place when higher temperature 'pockets' of fluid give up energy to lower temperature pockets with which they make contact as such motion occurs (Tucker, 1999). Usually in fire situations, convective heat transfer involves hot gases from a fire moving past a solid object that is initially cool, and transferring heat or energy to it. The heating rate depends on the velocity of the fluid at the surface of the solid, thermal properties of the fluid and solid and the temperature of the solid.

The general formula for heat transfer by convection is given by:

$$q = h_c \Delta T \qquad 1.2$$

h_c can be calculated using heat transfer principles, using the properties of the fluid, and geometry of the solid. A typical value for h_c is standard fires is 25 W/m^{2}K, which is the value used in the SAFIR simulations and the spreadsheet calculations. If a hydrocarbon fire was being simulated, a h_c value of 50 W/m^2 K is the recommended value in the Eurocode (Buchanan 1999).

Conduction:

The conduction form of heat transfer involves interactions between free electrons in a solid material, or between multiple materials. It involves a direct physical contact of the surfaces, and occurs without any appreciable displacement of the matter, excluding displacement due to thermal expansion (Tucker 1999).

Unless analysing the temperature profile across a beam at an instant of time, conduction is not as important in heat transfer calculations from fire to unprotected steel as the other modes of heat transfer. For most protected steel beams, however, the predominant mode of heat transfer to and from the steel is through conduction, as the steel is not exposed to radiation from the fire, or the hot gases generated by the fire. Steel beams with box protection do experience radiation and convection, not from the fire, but from the hot inner surface of the insulation board as well as conduction from the edges of the steel in contact with the insulation board.

1.6.2 Thermal Properties of Steel:

Various literature searches show that all agree that the thermal and mechanical properties of steel change with varying temperature. The strength of steel, or the load bearing capacity of steel decreases dramatically with an increase in temperature experienced in fire situations, but generally the thermal properties of the steel are assumed to stay constant for simplicity in calculations. The specific heat, density and thermal conductivity do however vary with temperature, and although the difference does not usually effect the temperature of the steel found from analyses significantly, the differences should still be noted.

Specific Heat:
Of the thermal properties of steel, the specific heat has the largest deviation from a constant value. Stirland (Purkiss, 1996) suggested that the specific heat of steel, c_s, be taken as:

$$c_s = 475 + 6.010x10^{-4} T_s^{\,2} + 9.46x10^{-2} T_s \qquad 1.3$$

This equation is valid for temperatures of the steel, T_s,, up to around 750 °C when the specific heat of steel reaches a discontinuity which occurs due to a phase change at the molecular level of steel at this temperature.

For the analyses performed here, and in most fire situations, this temperature is too low as the upper limit, so the equations used in this report are found in ENV 1993-1-2, as follows:

$$c_s = 425 + 0.773T_s + 1.69x10^{-3} T_s^{\,2} + 2.22x10^{-6} T_s^{\,3} \qquad 20 \le T_s < 600 \text{ °C} \qquad 1.4a$$

$$c_s = 666 - {13002}\big/{(T_s - 739)} \qquad 600 \le T_s < 735 \text{ °C} \qquad 1.4b$$

$$c_s = 545 + {17820}\big/{(T_s - 731)} \qquad 735 \le T_s < 900 \text{ °C} \qquad 1.4c$$

$$c_s = 650 \qquad 900 \le T_s < 1200 \text{ °C} \qquad 1.4d$$

There are other formulas that are valid up to the discontinuity at around 750 °C, and these are listed in various publications. Vandamme and Janss derived the following relationship (Proe et al 1986):

$$c_s = 3.8x10^{-4} T_s^{\,2} + 0.2T_s + 472 \qquad 1.5$$

A graph of the specific heat using these equations is shown below in Figure 1.1:

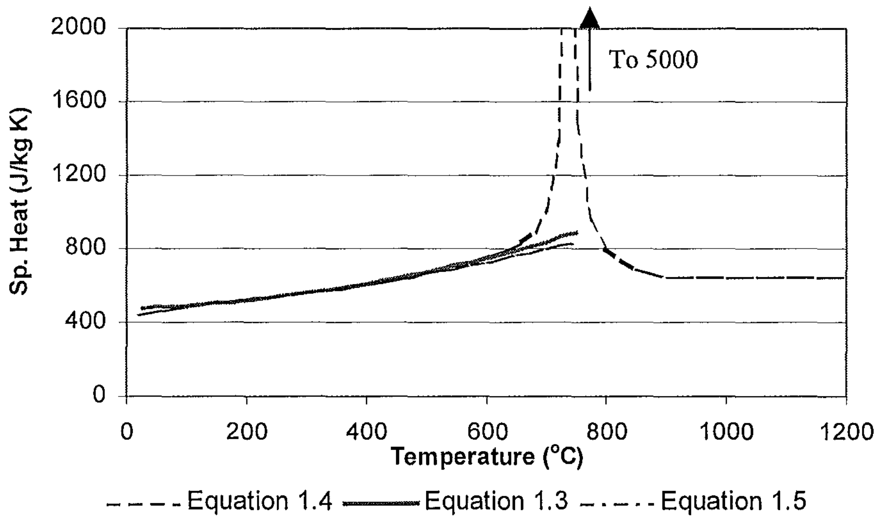


Figure 1.1: Variation of the specific heat of steel with temperature.

This discontinuity at around 750 °C corresponds to a phase change of steel when the steel changes from ferrite to austenite. The increase in specific heat reflects the latent heat of transformation (Gilvery and Dexter, 1997).

Purkiss, (1996) also states that a constant value of 600 J/kg K can be used for the specific heat of steel, which is commonly used in spreadsheet analyses and simple hand calculations. The British Steel Code recommends a constant value of 520 J/kg K.

Harmathy, (1996), suggests using known formulas for the specific heat of steel of the different components of steel, such as Ferrite, Austenite and Cementite. This is more complicated, however if the exact mixture of the steel is not known which is likely to be the case for designers.

Thermal Conductivity:

The thermal conductivity of steel varies slightly between different grades of steel, and with changes in the temperature of the steel. The difference between the grades of steel is not very significant, and ENV 1993-1-2 gives the following equation for the thermal conductivity of steel, k_s, where T_s is the temperature of the steel (°C).

$$k_s = 54 - 0.0333T_s \qquad \text{for } T_s \leq 800°C \qquad 1.6a$$

$$k_s = 27.3 \qquad \text{for } T_s \geq 800°C \qquad 1.6b$$

The thermal conductivity is not important in this report as we are concerned with the average and maximum temperatures found in the steel beams, which will relate to the strength of the beam. In the SAFIR programme the thermal conductivity of the steel is present because conduction takes place between the elements of the cross section, however the average temperature is not influenced by the thermal conductivity and it is not present in any equations used in this report. The thermal conductivity of the insulation when applied is important as this gives information on the transfer of heat to the steel beam.

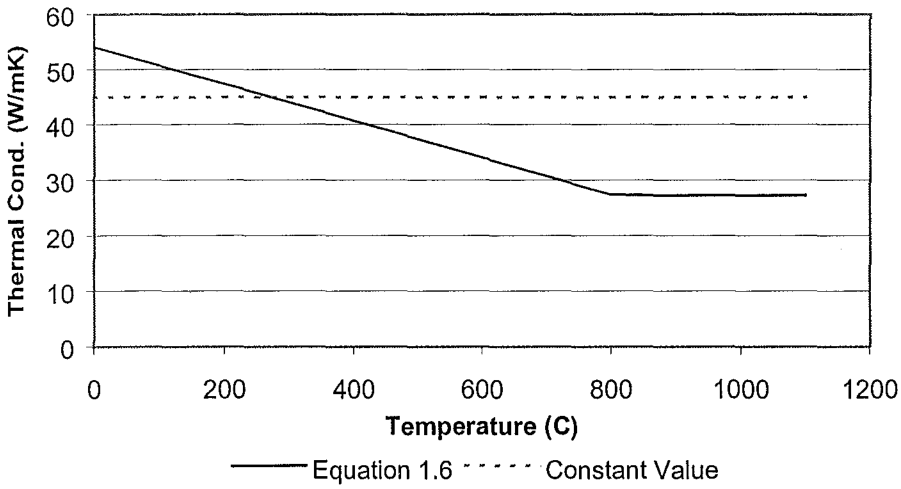


Figure 1.2:Variation of thermal conductivity of steel with temperature

For approximate calculations, the thermal conductivity of steel may be taken to be k_s = 45 W/mK, (Purkiss 1996), which is also recommended in Eurocode 3 and BS 5950:Part 8.

Density:

The density of steel is recommended by Purkiss, (1996) to remain at a value of 7850 kg/m^3 for all temperatures normally experienced during a fire, so this value has been used throughout this report.

Thermal Expansion:

When heated, steel expands linearly at a rate of:

$$\frac{\Delta l}{l} = 1.4x10^{-5} T_s \qquad 1.7$$

where the temperature of the steel, T_s is in °C, (Purkiss, 1996, BSI, 1990, EC3 1995). This value can vary as Harmathy, (1993), uses a value of 1.14 rather than 1.4. ENV 1993-1-2 also adopts a more variable approach to the thermal elongation of steel, with the following relationship between thermal elongation and temperature:

$$\frac{\Delta l}{l} = 1.2x10^{-5}T_s + 0.4x10^{-8}T_s^{\,2} - 2.416x10^{-4} \qquad 20 < T_s < 750\ ° \qquad 1.8a$$

$$\frac{\Delta l}{l} = 1.1x10^{-2} \qquad 750 < T_s < 860\ °C \qquad 1.8b$$

$$\frac{\Delta l}{l} = 2x10^{-5}T_s - 6.2x10^{-3} \qquad 860 < T_s < 1200\ °C \qquad 1.8c$$

The variation of these formulas with temperature are shown in Figure 1.3.

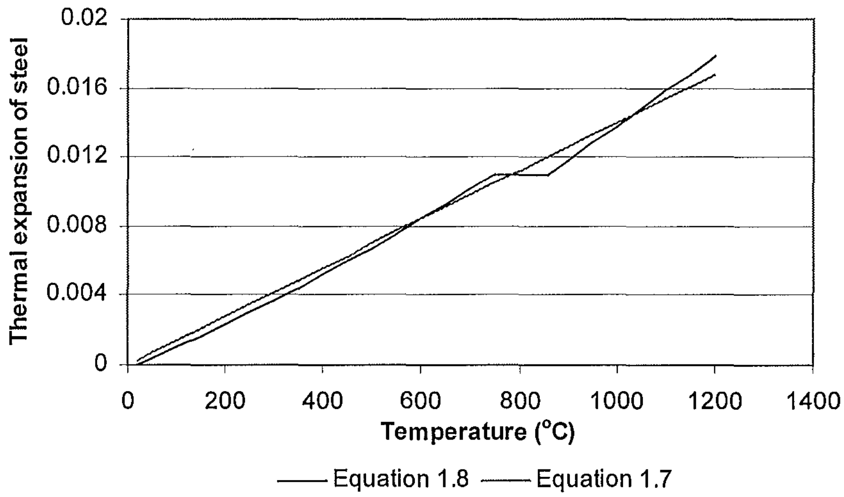


Figure 1.3: Variation of thermal expansion of steel with temperature

1.6.3 Section Factor, H_p/A:

The ratio of the heated perimeter to the cross sectional area gives the inverse of the effective width of the steel member. This term is called the Section Factor (SNZ, 1991). Throughout this report the notation used is H_p for the heated perimeter and A for the cross sectional area. Other notations include F for the heated perimeter, or the same ratio can be achieved in a three dimensional sense with the heated area per unit length to the volume per unit length used instead, A/V. Here A for heated surface area should not be confused with A of cross sectional area used in this report.

The heated perimeter of the steel member varies depending on the protection applied to the member, ie sprayed protection which has the section profile or board protection which boxes the section. When the member is exposed to the fire on less than four sides the ration can be calculated according to the table below. The cross sectional area is always the area of the steel section. The UK and international practice is also to use these values.

An alternative method of giving the general size of the beam with a single value is the Australian method of the ratio if exposed surface area to mass per unit length. This value gives the same information as the H_p/A value, with a constant factor of 7.85, which is the density of steel in tonnes/kg^3.

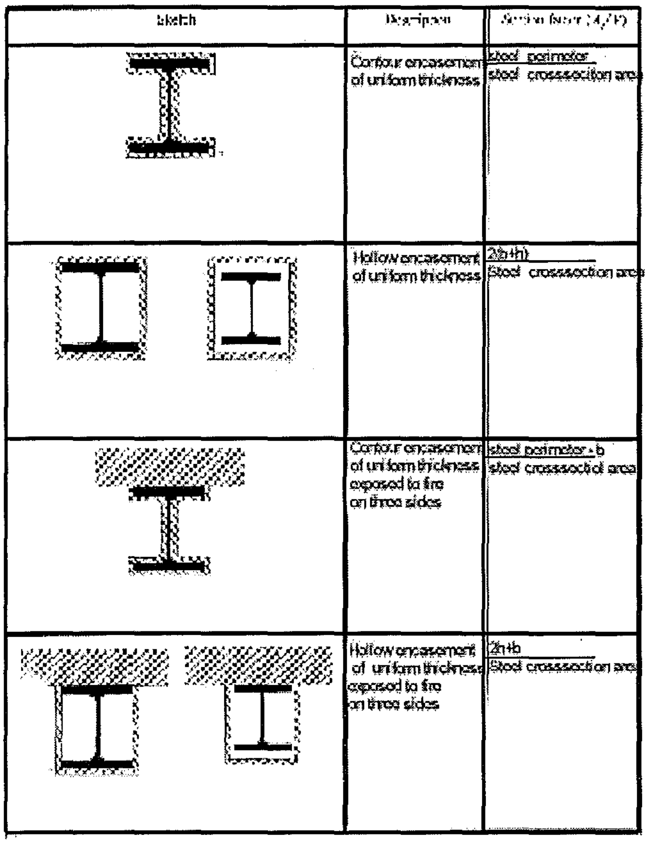


Figure 1.4: Variations of Hp/A for different methods of protection, (EC3 1995).

Many publications give the H_p/A value for a range of beam sizes, but the calculation is not difficult using the width and depth of the beam, if the radii and fillets of the section are ignored.

1.6.4 Methods of steel protection:

There are many passive fire protection means available to reduce the temperature rise of steel members when exposed to elevated temperatures. The fire resistance of these are often calculated using heat transfer principles and properties of the protection but these should be backed up with test results to determine the actual behaviour of the product in place

Some common forms of protection for steel, and methods to increase the fire resistance of steel members are listed below. The methods used in this report are the spray on and board protection.

Spray-on Insulative Protection:

This method of protecting steel is usually the cheapest form of passive fire protection for steel members. These materials are usually cement based with some form of glass or cellulosic fibrous reinforcing to hold the material together, (Buchanan, 1999). The disadvantages of spray on materials are that the application is wet and messy and the finish is not architecturally attractive. However this is not usually a problem for structural members that are hidden with suspended ceilings and partitions. The other important aspect of this insulation is the 'stickability' of the material, or how well the material stays in contact with the steel member at normal and elevated temperatures. If the insulation falls off the steel it obviously no longer is protecting the steel so the cohesion and adhesion of spray on protection must be thoroughly tested.

Board Systems:

Most board systems that are used to increase the fire resistance of steel members are made out of calcium silicate or gypsum plaster. Calcium silicate boards are made of an inert material and the board can remain in place for the duration of the fire. Gypsum plaster board has good insulating properties, and its resistance to elevated temperatures is improved with the high moisture content present in the board, which must be evaporated at 100 °C before the board further increases in temperature. This gives a time delay when the board reaches 100 °C, but reduces the available strength in the board after the water has evaporated.

The advantages of board systems are that they are easy to install and can be attractively finished. The boards can be fixed hard against the steel member or with a void between the inner face of the board and the steel section, See Figure 1.4.

Other Protection Methods:

Other protection systems that are often used in construction to increase the fire resistance rating of steel members include concrete encasement, intumescent paint, concrete filling, water filling and flame shields for external steelwork. Concrete encasement, concrete filling and water filling protection systems are based on the same protection principles. They decrease the rate of the temperature rise of steel by absorbing heat energy from the steel. Concrete and water filling are used for hollow steel sections, while concrete encasement has an I-beam surrounded by concrete.

Intumescent paint is a special paint that swells into a thick char when it is exposed to higher temperature, providing protection to the steel beneath. This allows the structural members to be attractively exposed but is more expensive than other systems.

2 FIRES AND THERMAL ANALYSIS COMPUTER MODELS:

2.1 SPREADSHEET METHOD:

2.1.1 Introduction:

The spreadsheet method of predicting the temperature of a steel beam uses principles from heat transfer theory to estimate the energy being transferred to the steel beam, and therefore the rate of temperature rise. The methods for protected and unprotected steel members are basically the same, with different formulas used to allow for the effect the protection has on the rate of heating of the steel. The method is recommended by the European Convention for Constructional Steelwork (ECCS, 1993), to establish a procedure of calculating the fire resistance of elements exposed to the standard fire, while a lot of the research and calibration with test data was done in Sweden, (Gamble, 1989).

The method is a one-dimensional heat flow analysis that accounts for the properties of the insulation as well as the area to perimeter ratio of the section, (Gamble, 1989). The temperature of the beam can be calculated at each time step, by considering the energy that the beam is subjected to during the previous time interval. The duration of the time step does not significantly effect the calculated temperatures. Petterson et al, (1976), suggest a time step so that there are 10 to 20 time steps until the limiting temperature of the steel is reached, and Gamble (1989), uses a time step of 10 minutes. For the analyses in this report, a time step of 1 minute is used for the majority of the calculations as the speed and capabilities of modern computers requires very little more effort to decrease the time step period to this.

The spreadsheet method assumes the steel member is of constant thickness governed by the H_p/A value. This is called a lumped mass approach as no regard is given for the actual geometry of the cross section. Constant values for the thermal properties of the steel such as the specific heat and density, are generally used to simplify the method and number of variables in the spreadsheet.

The values for the thermal properties of the steel and geometry of the shape are averaged values and not necessarily exactly what the member will be when constructed in place. This means that high accuracy is unnecessary and often inappropriate when many other factors, such as the temperature of the fire are also estimated.

The advantages of the spreadsheet programme are that the computer software that is required for it is a spreadsheet programme such as Microsoft Excel, which is installed in most office computers. For computer programmes such as SAFIR, files such as beam sizes, are required as well as the three units of the programme. With the estimations and assumptions made in fire design and analysis ,the 5 % difference found between the two methods can not show that one is more accurate than the other. Since the spreadsheet method usually gives higher temperatures than the SAFIR and other finite element programmes, the results are acceptable to use in design with four sided exposure and when analysing the temperature elevation of simply supported members.

2.1.2 Unprotected Steel:

The temperature of unprotected steel is found from the following method, (Buchanan, 1999):

Time	Steel Temp T_s	Fire Temp T_f	$T_f - T_s$	h_t	ΔT_s
$t_1 = \Delta t$	Initial steel temp, T_{so}	Fire Temp at $\Delta t/2$	$T_f - T_{so}$	Eqn 2.2 with T_s and T_f from this row	Eqn 2.1
$t_2 = t_1+\Delta t$	$T_s + \Delta T_s$ from previous row	Fire Temp at $t_1 + \Delta t/2$	$T_f - T_s$	Eqn 2.2 with T_s and T_f from this row	Eqn 2.1
etc	etc	etc	etc	etc	etc

Figure 2.1: Spreadsheet calculation for heat transfer in unprotected steel members, (Buchanan, 1999)

The difference in temperature of the steel over the time period is calculated from:

$$\Delta T_s = \left(\frac{H_p}{A}\right)\left(\frac{h_t}{\rho_s c_s}\right)(T_f - T_s)\Delta t \qquad 2.1$$

where H_p/A is the section factor of the beam (m^{-1})

ρ_s is the density of steel (kg/m^3)

c_s is the specific heat of steel (J/kg K)

Δt is the time step (min)

Using an initial time step of 1 minute gives a temperature of the steel of 20°C for 2 minutes before the curve starts to rise, which makes comparisons at the start of the test difficult. The time steps can be made smaller to allow slightly greater accuracy and a quicker reaction to the rise in atmospheric temperatures. In this report the time step is reduced to 0.2 minutes, (12 secs) for the first 2 minutes, then increased to 0.5 minutes, (30 seconds) for a further 4 minutes, and then increased to a final time step of 1 minute. This makes a significant difference to the temperature rise at the start of the ISO 834 fire curve as the fire increases in temperature dramatically during the early stages of the fire. Changing the time step in the early stages of the fire does not affect the fire or steel beam temperatures during the latter stages of the fire.

The total heat transfer coefficient, h_t, is the sum of the radiative and convective heat transfer coefficients, h_r and h_c. The value of the convective heat transfer coefficient, h_c, used in this report is 25 W/m^2 K as recommended by the Eurocode for standard fires, (Buchanan 1999). Since the radiative heat transfer depends on the temperatures of the steel element and its surroundings, this component of the total heat transfer coefficient must be calculated at each time step, using the following formula:

$$h_t = 25 + \sigma\varepsilon \frac{\left(T_f^{\,4} - T_s^{\,4}\right)}{\left(T_f - T_s\right)} \qquad 2.2$$

where σ is the Stefan-Boltzman constant (5.67 x 10^{-8} kW/m^{2}K^4)

ε is the emissivity for the fire

The Eurocode recommends using a value of 0.56 for the emissivity, but for this project a value of 0.5 has been used as this is the default setting in the SAFIR programme, and is recommended by other authors (Martin and Purkiss, 1992)

2.1.3 Protected steel:

The method for determining the temperatures of the steel in beams that have fire protection applied to them is very similar to that outlined in Section 2.1.2 for unprotected beams, but with different formulas to account for the effect that the insulation has on the rise of the steel temperature. By assuming that the exterior surface of the insulation is the same temperature as the surroundings, ie. the same temperature as the fire, a heat transfer coefficient is not required. This method also assumes that the steel is at the same temperature as the internal surface of the insulation.

The change in temperature of protected steel over a time period is given by:

$$\Delta T_s = \left({H_p}/{A} \right) \left(k_i / d_i \rho_s c_s \right) \left\{ \rho_s c_s / \rho_s c_s + 1/2 \left({H_p}/{A} \right) d_i \rho_i c_i \right\} \left(T_f - T_s \right) \Delta t \qquad 2.3$$

where d_i is the thickness of the insulation (m)

ρ_i is the density of the insulation

c_i is the specific heat of the insulation

To perform the spreadsheet analysis, a table is set up similar to Figure 2.1, without requiring the column for the heat transfer coefficient, and replacing equation 2.1 with equation 2.3.

EC3 (1995), recommends a slightly different formula for equation 2.3, where a 3 is used instead of the 2 in the brackets {}, and also includes an extra term to account for the increase in fire temperature over the time step Δt, (Buchanan, 1999). See Section 5.7 for more detail on alternative methods of estimating the temperatures of protected steel by a time step method.

The middle term in brackets, {}, accounts for the heat or energy absorbed by the insulation and is valid more for 'heavy insulation'. To determine whether the protection will absorb much heat as to significantly affect the temperature of the steel, ECCS, (1985), suggests calculating whether the heat capacity of the insulation is more than half the heat capacity of the steel, using the following formula:

$$\rho_s c_s A_s > 2 \rho_i c_i A_i \qquad 2.4$$

If the above equation is true then the insulation can be considered 'light' and the heavy insulation term in brackets, {}, can be omitted to simplify the equation. To see the effect of this omission, refer to Section 5.3.1.

2.2 ALTERNATIVE FORMULATIONS OF THE SPREADSHEET METHOD:

There are alternatives to the spreadsheet method as primarily used in this report. The method used in this report and described in Section 2.1, based on the principles of heat transfer, was developed by the European Convention for Constructional Steelwork (ECCS, 1983). The formula for protected steel, with heavy insulation is as below:

$$\Delta T_s = \left({H_p}/{A} \right)(k_i / d_i \rho_s c_s)$$

$$\left\{ \rho_s c_s / \rho_s c_s + {1}/{2} \left({H_p}/{A} \right) d_i \rho_i c_i \right\}$$

$$(T_f - T_s)\Delta t$$

For light, dry, or relatively thin insulation, the middle term in {} brackets can be negligible and therefore ignored.

Another method as recommended by ECCS in earlier work gave the following two formulas for light and heavy insulation. The heat flow to insulated steelwork was divided into these classes because the formulas used for heavy insulation gave unstable results when the insulation was termed 'light' from equation 2.4. The method for heavy insulation can not be justified on theoretical grounds, but the formulas have been included here for completeness, (Purkiss, 1996). The light insulation equation is the same as stated above with the heat capacity term neglected.

Light insulation:

$$\Delta T_s = \left(\frac{k_i}{d_i c_s \rho_s} \right) \left(\frac{H_p}{A} \right) (T_f - T_s)\Delta t \qquad 2.5$$

and for heavy insulation:

$$\Delta T_s = \left(\frac{k_i}{d_i c_s \rho_s}\right)\left(\frac{H_p}{A}\right)\frac{(T_f - T_s)\Delta t}{\left(1+\phi/2\right)} - \frac{\Delta T_f}{\left(1+2/\phi\right)} \qquad 2.6$$

where $\phi = \left(\frac{c_i \rho_i}{c_s \rho_s}\right) d_i \left(\frac{H_p}{A}\right)$ 2.7

The formula for heavy protection is the same as the spreadsheet used in this report, expect for the final term accounting for the change in temperature of the fire over the time period.

The time step Δt can be defined as: $\Delta t \leq \frac{25000}{\left(\frac{H_p}{A}\right)}$

By rearranging this equation, H_p/A must be greater than 416 m^{-1} with a time step of 60 seconds, which covers most beam sizes.

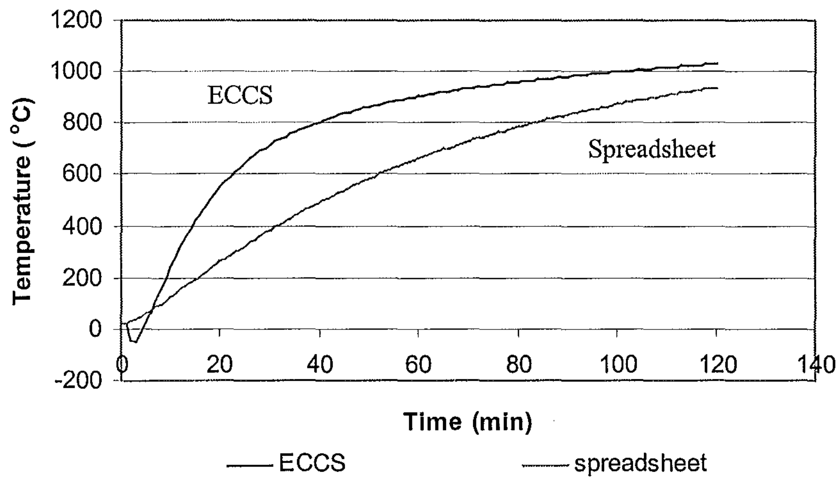


Figure 2.2: Comparison between the ECCS formula, equation 2.6, and the spreadsheet method for heavy insulation

Figure 2.2 above shows that there is quite a substantial difference in the estimated steel temperature from the ECCS and spreadsheet methods. The ECCS formula shows unstable behaviour at the start of the test, and the results are significantly higher than the results found from the spreadsheet method used throughout this report. The equation for light insulation with this method is the same as that given by the spreadsheet method with the heat capacity of the steel neglected.

Eurocode 3, ENV 1993-1-2 gives the following method, which was derived by Wickstrom:

$$\Delta T_s = \left(\frac{k_i}{d_i c_s \rho_s}\right)\left(\frac{H_p}{A}\right)\frac{(T_f - T_s)\Delta t}{1+\phi/3} - \left(e^{\left(\frac{\phi}{10}\right)} - 1\right)\Delta T_f \qquad 2.8$$

where ϕ is as defined above, and ΔT_f is the change in fire temperature over the time step.

The time step limit in seconds for this case can be defined as follows:

$$\Delta t = \frac{c_s \rho_s}{k_i}\left(1+\frac{\phi}{3}\right)\left(\frac{A}{H_p}\right) < 60 \qquad 2.9$$

A time shift is often used to account for the delay time provided by the presence of the insulation which would allow for the heat capacity of the insulation, as in the time that it takes the insulation to heat up. This time shift can be described by either of the methods shown below:

$$\bar{t} = \frac{\phi}{8}\left(\frac{A}{H_p}\right)\left(\frac{c_s \rho_s d_i}{k_i}\right)\left(1+\frac{\phi}{3}\right) \qquad \text{from Wickstrom} \qquad 2.10a$$

or

$$\bar{t} = \left(\frac{\phi}{6+2\phi}\right)\left(\frac{A}{H_p}\right)\left(\frac{c_s \rho_s d_i}{k_i}\right)\left(1+\frac{\phi}{3}\right) \qquad \text{from Melinek and Thomas} \qquad 2.10b$$

The differences between these two equations can be seen in Figure 2.3 below:

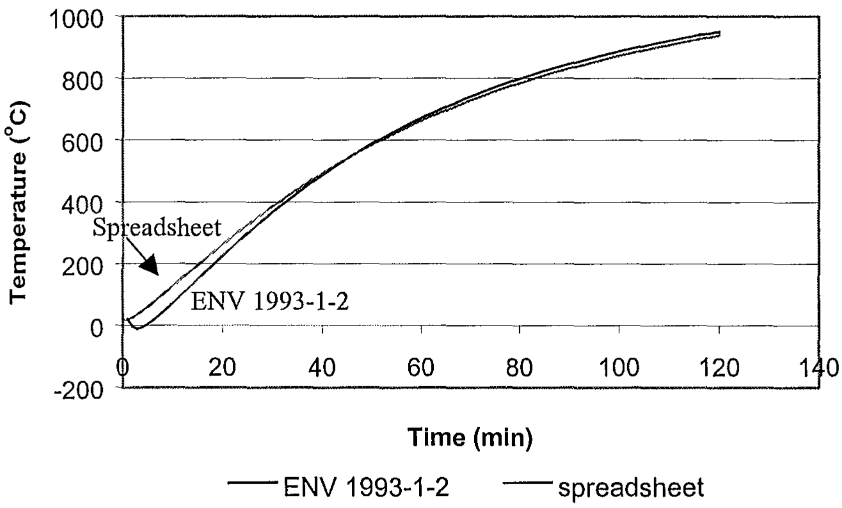


Figure 2.3: Comparison between the EC3 formula, equation 2.8, and the spreadsheet method

This method give results that are very close to those found from the spreadsheet method. The ENV formula gives a slight dip at the start of the test similar to the curve from the ECCS equation, but of much smaller magnitude. The curve then follows the spreadsheet method very closely, with the maximum difference between the temperature being less than 15 °C, and less than 2 % difference.

The time shift equations have not been accounted for in Figure 2.3 from either of the equations provided here, and the time step used is 60 seconds as this is the time step generally used throughout this report. The formulas differ by a term which accounts for the increase in fire temperature over the time step of the spreadsheet, ΔT_s, and a factor of one third in the insulative heat capacity term rather than one half as used in the spreadsheet equation.

The beam size used for these comparisons is the BHP-180 UB 16.1 with *Fendolite* spray on protection. The properties of this protection can be found in Section 5.2. Both of the alternative solutions in this section have an unstable beginning to the simulation as seen in Figure 2.2 and Figure 2.3, with negative temperature values of the steel being found. The temperatures from both methods stabilise however and increase in a similar fashion to the spreadsheet method.

2.3 THERMAL ANALYSIS PROGRAMMES:

There have been many computer packages designed to estimate the temperature of steel members when exposed to elevated temperatures. Some of these programmes have been specifically produced for fire analyses while others are structural programmes with temperature functions or options included into it. In this report the computer programme 'SAFIR' has been used extensively to compare the temperatures against the spreadsheet method, and to compare results found from 'real' experimental fire results.

2.3.1 SAFIR:

SAFIR is a finite element computer programme developed by Jean-Marc Franssen at the University of Liege, Belgium, (Gilvery & Dexter, 1997). It analyses structures under ambient and elevated temperature environments, and can study one, two or three-dimensional structures. SAFIR can perform structural or torsional analyses of complex framed buildings, or heat transfer analyses of cross sections of steel beams with or without insulate protection, (Nwosu, et al, 1999). In this project the SAFIR capabilities has been limited to the thermal analyses of steel beam cross sections. The thermal properties change with temperature as programmed into the computer package, and these vary as recommended by EC3. Refer to Section 1.6.2 for these equations.

The analysing process of a cross section of a steel beam, through SAFIR is as follows:

Wizard/Pre-processor

In this computer package the details of the cross-section of the beam are entered in a graphic layout, and the properties of the insulation, if appropriate, are added. The required time step, and the type of output is requested. Other options to add or edit at this stage are the initial temperature; integration and calculation parameters and accuracy and re-numbering of equations time discretisation. Output can be either in the form of temperatures of the nodes, or the average temperature of the elements at each time step.

The pre-processor therefore, creates *.str and *.dat files which the SAFIR programme requires for an analysis of a cross section of an element. The *.str files contains information regarding the geometry of the cross section, the placement of the nodes and elements and the exposed edges to the fire. The *.dat files contain the calculation information such as the integration accuracy and length of the time step.

Types of cross sections that can be analysed include unprotected members; protected members with up to three types of insulation, and whether the beam supports a concrete slab. Changes to the number of elements being analysed can be made to increase or decrease the accuracy. The user also defines the type of fire that the element is subjected to and which faces of the element are exposed to the fire.

The wizard programme was developed by G. Ionica and Y. Vanderseipen in 1998, under the supervision of Dr J-M. Franssen at the University of Liege. The Pre-processor developed by John Mason has more functions including options for box protection, and for user defined fires. The alternative pre-processor by Mason (2000) has been the primary tool in setting up files for SAFIR to analyse in this project.

SAFIR

The SAFIR programme can calculate a thermal analysis of a cross section, which is what it has been required to do in this project. If a more complex structure, rather than just a cross section had been analysed, then SAFIR would break the structure into smaller sub-structures and perform temperature calculations for each sub-structure, performing first a 2-D SOLID element analysis and using this information to give a 3-D result. Therefore with a two dimensional model, all that is required by SAFIR is to perform heat flow calculations around the element cross section.

The SAFIR programme creates *.out, *.log and either *.tem or *.tnd output files. *.out files contain all information regarding the structure, including what is found in the *.str and *.dat files, together with the temperatures of the nodes at each time step and the energy received by the cross section element. *.tem and *.tnd files are files with the temperatures of the elements or nodes recorded at each time step respectively.

Diamond

The Diamond programme is a post processor of SAFIR, that reads the output files, *.out, generated by SAFIR and displays the results of the analysis in a graphical and pictorial form. Diamond can generate a time temperature curve for each node because the temperature of each node is evaluated at each time step and included in the *.out files. This means that the temperature rise of different nodes across the cross-section can be observed with time.

At each time step calculated by SAFIR, the temperature over the cross section of the element can be shown either by block colours or with contour lines and the user can choose the range of temperature values.

2.3.2 Firecalc:

Firecalc is a software package that incorporates 24 different fire analysis tools to determine the behaviour of fires and fire systems. Some of the functions include the response times of sprinklers or smoke detectors, plume filling rates and egress times from rooms, (CSIRO, 1993).

The function applicable to this report is 'Steel Beam Load Bearing Capacity' which has output providing the temperature of the standard fire, the temperature of a chosen steel beam and the proportion of original or ambient strength the steel beam still has after 18 minute time intervals. The programme has the capacity to simulate unprotected steel beams with box or spray on protection. The user can also choose whether a ceiling slab is present. The inputs required are the weight per unit length and perimeter of the beam and the thermal properties of the insulation. This programme is designed specifically for three sided exposure to fire with a concrete slab and using the programme for other beam configurations is not recommended.

An input option is included to specify the moisture content of the insulation, which provides a delay time at around 100 °C when the water is evaporated, as the insulation is able to absorb latent heat energy without increasing in temperature. Moisture also affects the flow of heat to the beam through the insulation, which is allowed for in this model.

The background for calculations made in this programme comes from heat transfer theory, from an emitter to a receiver. Radiation and convection are both considered when calculating the energy transmitted to the insulation using fundamental heat transfer equations. The coefficient for convective heat transfer is 83.6 kJ/m^2 hr K, which is equivalent to 23.2 W/m K. Information not specified in the user manual is the emissivity constant for radiation; the equation to evaluate the delay due to the moisture content, properties of steel and whether these vary with temperature.

The load bearing capacity of the steel beam is also calculated, which is given in a ratio form of a proportion of the initial load on the beam. The equation used to estimate the load bearing capacity of the beam at elevated temperatures is:

$$L = 905 - T/690 \qquad T_s > 215\ °C \qquad 2.11a$$

and $$L = 1.0 \qquad T_s \leq 215\ °C \qquad 2.11b$$

This equation originates from the yield stress proportion formula, which can be found in NZS 3404. The programme therefore assumes that the load bearing capacity of a member is directly proportional to the ratio of yield stresses at elevated temperatures to normal temperatures as is used in NZS 3404. Using this method eliminates the need to consider the safety factors and different loadings that the beam may have been designed for, and considers only the variation of the yield stress with temperature.

The moisture concept is not included in the SAFIR programme so for comparisons with the SAFIR results, this has been assumed to be zero for consistency, when using Firecalc.

2.4 FIRE CURVES:

2.4.1 Standard Fire – ISO 834:

The standard fire is a fire that is used to perform tests on building materials and structural elements. The ISO 834 fire is the standard fire most commonly used in New Zealand. The formula for this fire is:

$$T = 345\log_{10}(8t+1) + T_0 \qquad 2.12$$

The time-temperature curve of the ISO 834 fire is shown below:

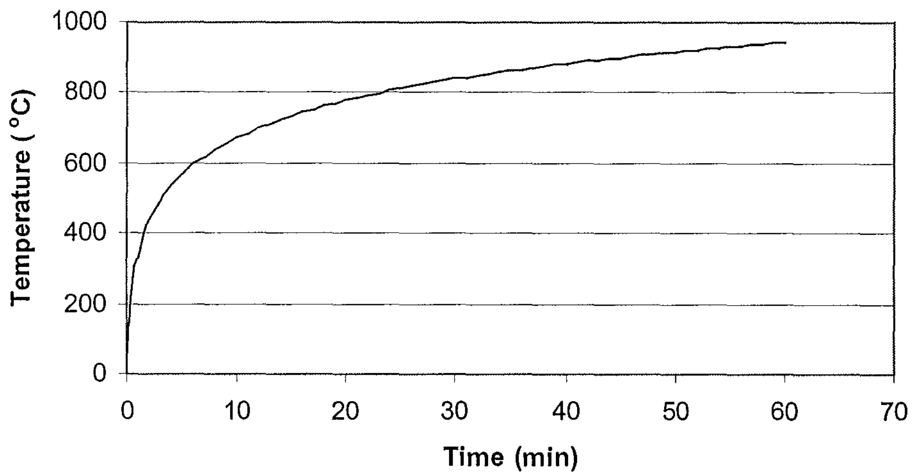


Figure 2.4: Time temperature curve of the ISO 834 Standard Fire Curve

The standard fire is primarily used in experimental fire tests, as although it does not resemble a 'real' fire, it can be replicated in a controlled environment. By using a standard fire, manufacturers can test their product and find a fire resistance time that can be compared to other building products. Since all products are tested and exposed to the same fire they can be compared due to the consistency in the tests.

The temperature of the standard fire continues to increase with time, which is unrealistic. The temperature increases at a rapid rate at the beginning of the fire and then the increase in temperature slows down to reach a near constant temperature rise.

There are a number of procedures practiced that use the results from fire tests with a standard fire to estimate the behaviour of a member in a 'real' or likely fire. These include the Time Equivalent methods where the member can be considered to have undergone failure when either the temperature, the area under the time-temperature curve or the strength of the member is the same as that when the member was subjected to the ISO 834 fire.

The Standard ISO 834 fire is similar in temperature to the American standard fire, ASTM E119. The fires can be considered to give around the same thermal exposure but there are some significant differences in the regulations of performing the tests. The New Zealand, Australian and British fire codes use the ISO 834 fire as their standard fire so this has also been used in this report.

2.4.2 Eurocode Parametric fire:

The temperature of a typical room fire is a function of the ventilation available in the room, the fuel load in the room and properties of the wall linings of the compartment. The Eurocode Parametric fire has these factors and changing the parameters adjusts the slope of the curve, the maximum temperatures that are reached and at what time, and the duration of the heating phase. The Eurocode Parametric fires are more realistic than the ISO 834 fire because the fire does not continue increasing in temperature indefinitely, and the geometry and properties of the compartment the fire is in is taken into account.

The decay phase is more representative of a real fire because the fuel load in a compartment is always going to reduce during a fire, and therefore decrease the burning rate.

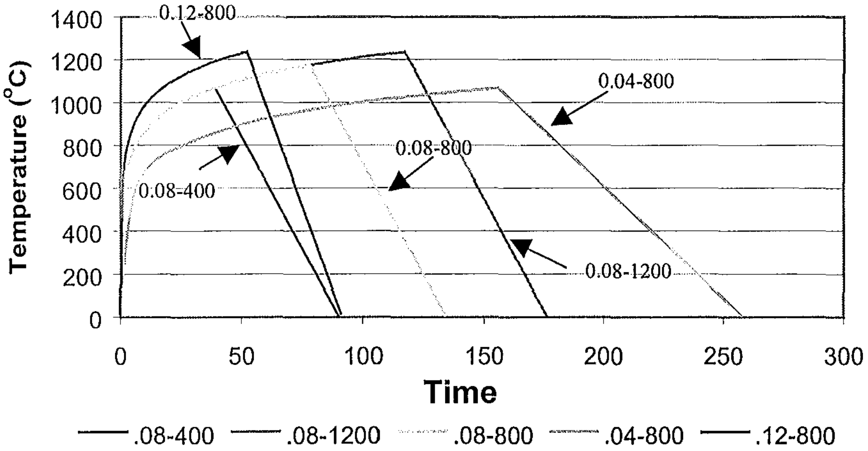


Figure 2.5: Eurocode fires with varying ventilation factors and fuel loads

Figure 2.5 shows the five Eurocode fires used in this report. The decimal value in the legend represents the ventilation factor and the second value represents the fuel load in MJ/m^2 in the compartment.

The Eurocode fire is formulated in two parts, namely the heating phase and decay or cooling phase.

The heating phase is governed by the following formula:

$$T = 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}) \qquad 2.13a$$

where t* is a fictitious time in hours given by:

$$t^* = t''\left(\frac{F_v}{0.04}\right)^2\left(\frac{1160}{\sqrt{k\rho c_p}}\right)^2 \qquad 2.13b$$

where t'' is the time in hours

F_v is the opening factor given by: $F_v = {A_v\sqrt{H_v}}/{A_t}$

A_v is the area of the ventilation openings (m^2)

H_v is the height of the opening (m)

A_t is the total internal surface area of the room (m^2)

$\sqrt{k\rho c_p}$ are the thermal properties of the wall lining materials ($J/m^2\,K\,s^{1/2}$)

The fire curve follows this formula for a time governed by the following formula:

$$t_d = \frac{0.00013e_t}{\left(A_v\sqrt{H_v}\middle/A_t\right)} \qquad 2.14$$

where e_t is the fuel load in the compartment (MJ/m^2 total surface area)

After the period of heating, t_d, has been completed the fire cools down linearly. Buchanan (1999), modified the original Eurocode method of decay because there appeared to be confusion between fictitious time and real time, and the Eurocode method gave excessive cooling rates with larger openings. Wickstrom suggested that the decay rates apply to real time, with cooling magnitudes of 625 °C for fires of duration of less than half an hour, decreasing to 250 °C for fires of greater than two hours duration, (Buchanan 1999)

For the purpose of this project the decay rate used will be as suggested by Buchanan:

$$\frac{dT}{dt} = 625\left(\frac{F_v}{0.04}\right)\left(\frac{\sqrt{k\rho c_p}}{1160}\right) \qquad 2.15$$

This is also the form of the decay rate equation that is used in the pre-processor developed by John Mason used in later sections of this report.

As seen in equations 2.7 a-b, the growth rate of the Eurocode parametric fire is independent of the fuel load in the compartment, which intuitively appears incorrect that the fuel load does not affect the temperature of the fire. Since the Eurocode Parametric fires are ventilation controlled, however, the fuel load does not affect the temperature rise, as the temperature is more dependent on the ventilation available to the fire. In the early stages of the fire, however, when the fire is more likely to be fuel controlled, the amount of fuel would affect the fire temperatures. Since for establishing the fire resistance of structural members the fire has a significant duration, this assumption of ventilation controlled fires is not inappropriate.

Since the Eurocode fire is a function of three variables, namely ventilation factor, fuel load and wall lining properties, there are a large number of possible fires to be formed when different values are used for each variable. To reduce the number of fires studied here, a standard case has been chosen, from which one variable is changed at a time. The value of the wall lining properties factor $\sqrt{(k\rho c_p)}$ is kept at a constant value of 1160 during all tests.

For the standard case, the ventilation factor is 0.08 and the fuel load is 800 MJ/m^2 of total surface area. The ventilation factor then varies to 0.04 and 0.12 and the fuel load varies to 400 and 1200 MJ/m^2 of total surface area.

Varying these dependants singly results in 5 different fire curves as shown in Figure 2.5.

3 Fire Section of the Steel Codes:

3.1 NZS3404/AS4100:

The New Zealand and Australian steel codes, (SNZ, 1997 and SAA 1990) are very similar in all sections of the codes, and this applies also to the fire design chapter. The layout and all formulas are alike so the two codes have been grouped together to reduce the repetitiveness of this report. This section is based on the New Zealand Steel Code and then compared with the equivalent method recommended by Eurocode 3.

3.1.1 Determination of Period of Structural Adequacy (PSA):

The PSA of a member is the time in minutes for a member to reach the limit state of structural adequacy when exposed to the standard fire test, and therefore is the time for which the structural member will support the applied loads when subjected to a standard fire test. PSA of a member is the time when subjected to the standard fire until failure.

> From NZS 3404:1997:
> The Period of Structural Adequacy (PSA) shall be determined using one of the following methods:
> a) By calculation:
>   i) By determining the limiting temperature of the steel (T_l) in accordance with 3.1.3; and then
>   ii) By determining the PSA as the time from the start of the test (t) to the time at which the limiting temperature is attained in accordance with 3.1.4 for unprotected members and in 3.1.5 for protected members; or
> b) By direct application of a single test in accordance with 3.1.6; or
> c) By structural analysis in accordance with Section 4, using mechanical properties, which vary with temperature in accordance with 3.1.2. Calculation of the temperature of the steel shall be by using a rational method of analysis, which has been confirmed by test data.

These rules are based on the element being strong enough to support its load if the temperature of the steel does not exceed a limiting temperature. This is a comparison in the time domain, where the element is considered to be structurally sound until a time when calculations estimate the member will fail.

The Eurocode does not define a method to calculate a time for structural adequacy of an element. It is instead based on the structural performance of a steel member at time t, which is an analysis in the strength domain. The corresponding design resistance at this time must be greater than the design action imposed on the element during the fire, i.e. $U_f^* \le R_f$

Where U_f^* is the design force applied on the structure during a fire at a given temperature and R_f is the load bearing capacity at that temperature.

Slightly different methods are given for tension and compression members, for bending and shear, and for different end conditions.

3.1.2 Variation of Mechanical Properties of Steel with Temperature:

Variation of Modulus of Elasticity with Temperature:

The mechanical properties of steel vary with temperature, generally decreasing as the temperature of the steel increases. Steel has a limited strength, meaning that at a certain temperature the strength of the member will decrease to virtually zero.

The equations for the variation of the modulus of elasticity adopted in the New Zealand and Australian codes are those recommended by the French Technical Centre for steel construction, CTICM, (Wong and Petterson, 1996). The advantage of using these equations is that they cover a large range of temperatures from 0 °C to 1000 °C.

The variation of the modulus of elasticity with temperature is given by:

$$\frac{E(T)}{E(20)} = 1.0 + \frac{T}{2000\ln\left[\frac{T}{1100}\right]} \qquad 0 < \mathrm{T} \le 600\ °\mathrm{C} \qquad 3.1a$$

$$= \frac{690\left(1 - \frac{T}{1100}\right)}{T - 53.5} \qquad 600 < \mathrm{T} \le 1000\ °\mathrm{C} \qquad 3.1b$$

Eurocode 3 gives values for the proportion of Modulus of Elasticity in a table with varying temperature. Figure 3.1 below shows the variation of the modulus of elasticity with temperatures as given by NZS 3404, Eurocode 3, and from ECCS, (Bennetts et al 1986).

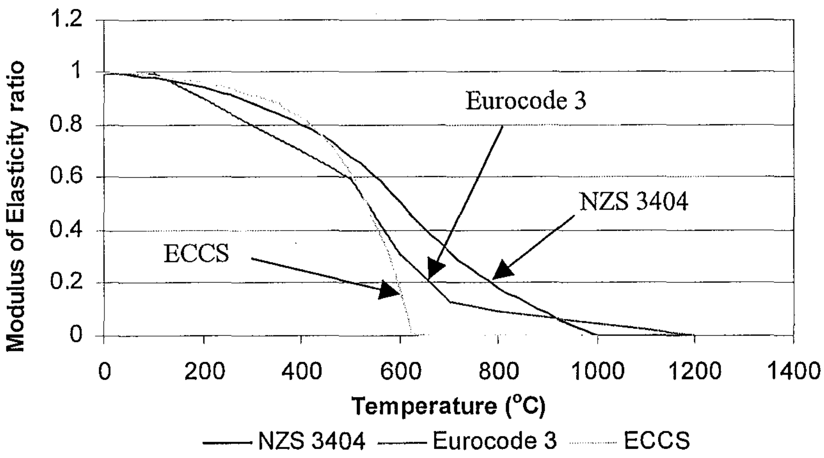


Figure 3.1: Variation of the Modulus of Elasticity with temperature as given by various sources.

The formula published by ECCS is given below in equation 3.2 but has been replaced by the data points recommended by the Eurocode, EC3.

$$\frac{E(T)}{E(20)} = 1 - 17.2x10^{-12}T^4 + 11.8x10^{-9}T^3 - 34.5x10^{-7}T^2 + 15.9x10^{-5}T \qquad 3.2$$

The temperature for which the modulus of elasticity reduces to zero is at a very low temperature of 625 °C for this ECCS equation, which is much lower than the zero strength. Comparing this limiting temperature with that of more recent studies suggests that this correlation is outdated. Recent studies such as that by Poh (1996), show that steel retains proportions of strength for temperatures up to 1000 °C.

Variation of Yield Stress with Temperature:

The following formula, equation 3.2 a-b, is given in the New Zealand and Australian codes for the variation of yield stress with temperature. These relationships are based on a regression analysis of data found from elevated temperature tensile tests performed in Australia and Great Britain, Proe et al, (1986). The variation of yield stress with temperature is generally considered independent of the steel grade, so one formula is valid for all grades of steel (Purkiss, 1996)

$$\frac{f_y(T)}{f_y(20)} = 1.0 \qquad 0 < T \le 215\ °C \qquad 3.3a$$

$$= \frac{905 - T}{690} \qquad 215 < T \le 905\ °C \qquad 3.3b$$

The ECCS recommended variation of yield stress with temperature follows the formulas given below in equation 3.4 a-b:

$$\frac{f_y(T)}{f_y(20)} = 1.0 + \frac{T}{767 \ln\left(T/1750\right)} \qquad 0 < T < 600\ °C \qquad 3.4a$$

$$\frac{f_y(T)}{f_y(20)} = 108 \frac{\left(1 - T/1000\right)}{T - 440} \qquad 600 < T < 1000\ °C \qquad 3.4b$$

The Eurocode again uses values in a table to show the variation of the yield stress with temperature. The difference between that given by NZS 3404 and the Eurocode are small and beyond the scope of this project to determine which, if either, is most accurate. Figure 3.2 shows the variation of the proportion of yield stress with temperature.

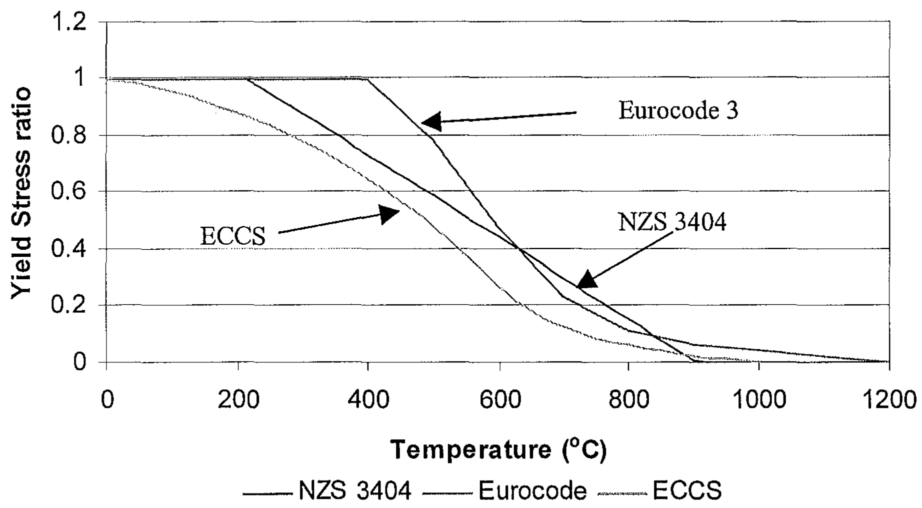


Figure 3.2: Variation of the yield stress of steel with temperature as given by various sources

The New Zealand Steel Code equations tend towards zero at a lower temperature than the other equations in Figure 3.2, for the proportion of strength remaining in steel at elevated temperatures. The ECCS equations propose a more severe loss of strength of steel than those recommended by CTICM, but also introduce a factor to adjust for this underestimate of strength, (Proe et al, 1986). This factor has not been considered in this report.

The temperature at which the proportion of the yield stress at elevated temperature is considered to have dropped to zero differs from that of the modulus of elasticity. Inwood, (1999), found this discrepancy in the New Zealand Concrete Standard, and suggested an adjustment to the curves so they tend to zero at the same temperature. This gives more reasonable results, as a zero yield stress can not occur when the modulus of elasticity has a value. The Eurocode 3 formulae, which give the variation of mechanical properties with temperature, tend towards zero at the same temperature of 1200 °C.

Comparing the Eurocode curves for the mechanical properties of steel with those obtained from the New Zealand Steel Code show that for the yield stress, the Eurocode gives generally less conservative or higher values, while for the modulus of elasticity the Eurocode 3 curves are more conservative and lower than those from NZS 3404.

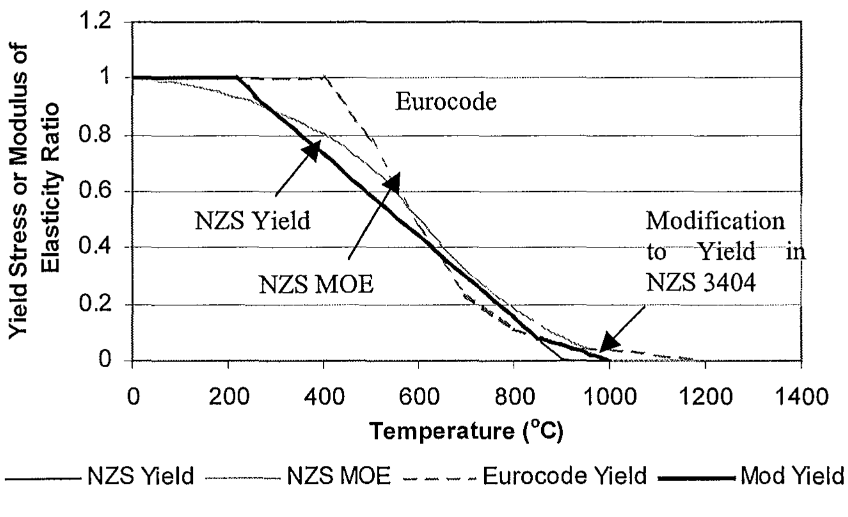


Figure 3.3: Variation of Yield Stress and Modulus of Elasticity with temperature

Figure 3.3 above shows the variation with temperature of the yield stress of steel as given by the New Zealand Steel Code and the Eurocode, and an adjusted line of yield stress from NZS 3404 so that the limiting temperature is 1000 °C. This temperature is chosen because it is the limiting temperature of the modulus of elasticity in the New Zealand Code. The original formula for yield stress is based on a regression analysis, Proe et al[1], (1986), of data at rather low temperatures, i.e. below 600 °C. Adjusting the slope therefore to have two linear lines work better, as this allows the formulae to give accurate estimates in the temperature range where the equation was formulated from, and by varying the higher temperature section of the relationship, allows the yield stress to drop to zero at the same temperature as the modulus of elasticity.

The Eurocode relationship between yield stress and temperature is much more varied than the linear relationship presently in the New Zealand Code, so an 'elbow' in the line of yield stress would not be an inaccurate concept.

The chosen deviation from the present equation in NZS 3404 starts when the temperature is 850 °C and the yield stress ratio is 0.08. This point is chosen as this is where the curve from the Eurocode intersects the NZS 3404 line, subsequently making the NZS 3404 line comparatively non conservative at temperatures greater than 850 °C. A straight line equation has then been formulated so that the yield strength drops to a value of zero at a temperature of 1000 °C. No experimental or other data, apart from the correlation with the Eurocode curve has been used to validate this approach.

The relationship between yield strength and temperature then becomes:

$$\frac{f_y(T)}{f_y(20)} = 1.0 \qquad 0 < \mathrm{T} \leq 215\ °\mathrm{C} \qquad 3.5a$$

$$= \frac{905 - T}{690} \qquad 215 < \mathrm{T} \leq 850\ °\mathrm{C} \qquad 3.5b$$

$$= 0.08\left(\frac{1000 - T}{150}\right) \qquad 850 < \mathrm{T} \leq 1000\ °\mathrm{C} \qquad 3.5c$$

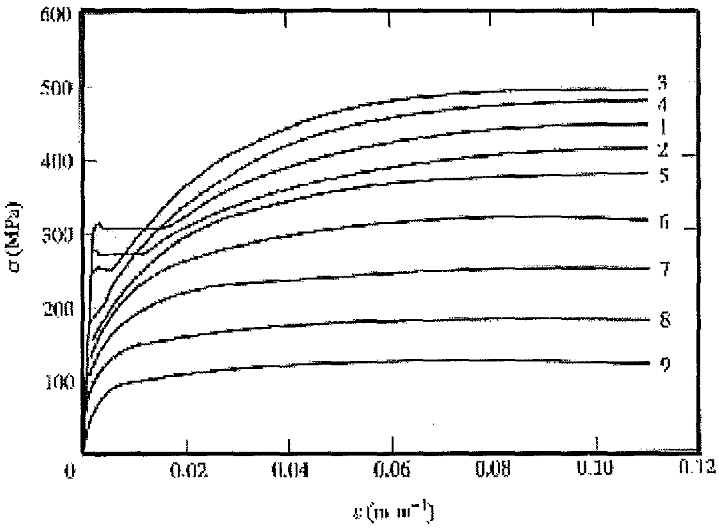


Figure 3.4: Stress strain curves with varying temperature. Curve 1.24 °C, 2. 99 °C, 3. 204 °C, 4. 316 °C, 5. 427 °C, 6. 482 °C, 7. 535 °C, 8. 593 °C, 9. 649 °C (Harmathy, 1993)

Figure 3.4 shows the variance in the stress-strain strain curve with temperature. Eurocode 3 has many curves on separate graphs showing this change in the stress strain relationship. The graph clearly shows the decrease in ultimate and yield stress of steel with temperature.

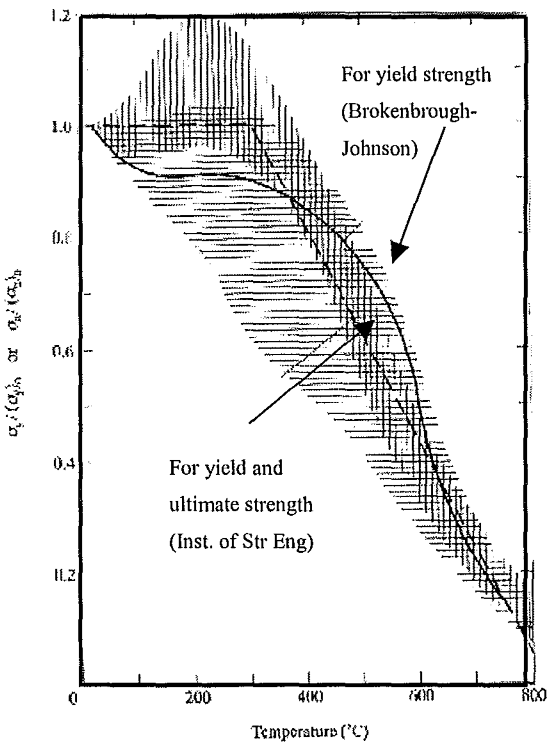


Figure 3.5: Variation of ultimate and yield strength of hot rolled steel, (Harmathy, 1993)

The variation of yield stress data is shown in Figure 3.5. This graph plots the variation in ultimate and yield strength of steel as taken from experimental data. The spread of data results as seen in this graph explains how difficult it is to compare the equations recommended by different parties, and choose one as being 'better' than another. Most data is found for temperatures below 600 °C, which is probably why there is greater spread in this region of the graph.

3.1.3 Determination of Limiting Steel Temperature:

The formula to determine the temperature at which the member being analysed will fail is a direct rearrangement of the formula for the variation of the yield stress of steel for temperatures over 215 °C. This implies that the only factor affecting the steel strength is the yield stress with temperature.

$$T_l = 905 - 690 r_f \qquad 3.6$$

where r_f is the ratio of the design action on the member under the design load for fire specified in NZS 4203, to the design capacity of the member at room temperature, ie $R_f/\phi R_u$. This formula can be used for three or four-sided exposure to fire, and for steel beams and columns.

The design capacity of the steel section is based on the yield stress and the cross sectional area of the beam, so assuming the cross section of the beam remains constant and a uniform temperature is maintained throughout the steel, then this formula is valid. This only occurs with four-sided exposure, as with three-sided exposure to a fire, there will be significant temperature differences across the cross section of the steel. When attempting to use this formula for three-sided exposure a finite element approach is used to obtain a limiting temperature that accounts for the temperature gradient in the steel.

Eurocode 3 has a different formula to calculate the limiting or critical temperature of a steel member. This method can be used as an alternative to the strength criteria that must be met as stated in 3.1.1. The critical temperature is based on the degree of utilisation of the element and is given by the following equation:

$$T_{s,cr} = 39.19 \ln\left[\frac{1}{0.9674\mu_0^{3.833}} - 1\right] + 482 \qquad 3.7a$$

or, for values of μ_0 from 0.22 to 0.80, the limiting temperature has been calculated and entered in a table. The degree of utilisation is a factor giving the ratio of design load to load bearing capacity of the member at elevated temperatures, and the same effecitve factor as r_f in NZS 3404.

When this equation is rearranged to produce a formula in terms of μ_0, this becomes:

$$\mu_0 = \left[0.9674\left(1 + \exp\left(\frac{T - 482}{39.19}\right)\right)\right]^{-1/3.833} \qquad 3.7b$$

Fitting the results from this equation against those in Figure 3.2 gives a curve that fits the data points included in the table in EC3. This is expected, as the calculation of the limiting temperature in NZS 3404 is a direct rearrangement of the yield stress formulas also.

3.1.4 Temperature rise of unprotected steel:

According to NZS 3404:1997

The time (t)at which the limiting temperature is attained shall be calculated for:

a. Three sided exposure as follows:

$$t = -5.2 + 0.0221T_l + \left(\frac{0.433T_l}{SF}\right) \qquad 3.8$$

b. Four sided exposure as follows:

$$t = -4.7 + 0.0263T_l + \left(\frac{0.203T_l}{SF}\right) \qquad 3.9$$

where: SF is the section factor of the steel member $\left(H_p/A\right)$, m^{-1}.

These formulas have limitations for the steel temperature and the section factor of the beam. These are:

$500 < T_l < 850$ °C in NZS 3404, and $500 < T_l < 750$ °C in AS 4100

$15\ m^{-1} < H_p/A < 275\ m^{-1}$ in NZS 3404 and AS 4100

To obtain times for temperatures below 500 °C, linear interpolation can be used with starting temperature of 20 °C.

These formulas were obtained from regression analyses of British temperature data for unprotected steel. Design temperatures for different fire resistance times for beams and columns are found in the British Steel Code, BS 5950: Part 8: 1990, which were used as the basis of the regression analysis. The upper temperature limit has been increased from its original value due to research performed in recent years, such as by Clifton and Forrest, (1996). The Australian code has not revised the upper temperature limit and this remains at 750 °C.

Eurocode 3 does not contain simple empirical formulas such as these, but rather gives a heat transfer formula to calculate the temperatures in a spreadsheet form. The formula is in a slightly different form than that stated in Section 2.1.2, but the same heat transfer principles are applied:

$$\Delta T_{s,t} = \frac{H_p/A}{c_s \rho_s} \dot{h}_{net,d} \Delta t \qquad 3.10$$

where $\dot{h}_{net,d}$ is the design value of the net heat flux per unit area (W/m^2). $\dot{h}_{net,d}$ replaces the variables in the spreadsheet formula and can be calculated by $\dot{h}_{net,d} = h_t \left(T_f - T_s\right)$ to give an equation of equivalent to the spreadsheet formula given in Section 2.1.2.

This method of estimating temperatures of unprotected steel gives the designer more freedom to evaluate the temperature time curve throughout the full ISO 834 fire exposure without any limitations to consider. The evaluation method is not difficult and once set up in a spreadsheet form, the results can be found very easily.

3.1.5 Temperature rise of protected steel:

The temperature rise of protected steel as specified in the New Zealand and Australian codes is to be based on results of tests on members with the appropriate protection. To evaluate the performance of a protected member, temperature data can be obtained from either a single experimental test or from regression data from a series of tests.

For all members with four sided exposure conditions, the limiting temperature is recommended by NZS 3404 to be taken as the average temperature of all results taken by thermocouples taken during the test. For columns with three sided exposure conditions, the limiting temperature is taken as the average temperature of the thermocouples located on the face furthest from the wall, or alternatively the temperatures from members with four sided exposure can be used for more conservative results.

NZS 3404:1997 states:

> The variation of steel temperature with the time measured in a standard fire test may be used without modification provided:
> a) The fire protection system is the same as the prototype;
> b) The fire exposure condition is the same as the prototype;
> c) The fire protection material thickness is equal to or greater than that of the prototype;
> d) The section factor is equal to or less than that of the prototype; and
> e) Where the prototype has been submitted to a standard fire test in an unloaded condition, stickability has been separately demonstrated.

When the results of a series of tests are to be used, the variation of temperature with time can be interpolated provided the tests meet the limitations provided in a) – e) above.

NZS 3404 also has an option to use a regression analysis to form a relationship between temperature and time by using the following formula:

$$t = k_o + k_1 h_i + k_2\left(\frac{d_i}{SF}\right) + k_3 T + k_4 h_i T + k_5\left[\frac{d_i}{SF}\right] + k_6\left(\frac{T}{SF}\right) \qquad 3.11$$

where:

t = time from start of the test (min)

$k_o - k_6$ = regression coefficients

d_i = thickness of fire protection material (mm)

T = steel temperature (°C), T>250 °C

SF =section factor of steel member, exposed surface area to mass ratio (m^2/t)

$$= \left(\frac{H_p / A}{7.85} \right) \ (\mathrm{m}^{-1})$$

The constants k_0 to k_6 are determined from tests to fit the data. For a particular insulation, the constants are determined by iterations to fit the available data, and then interpolation between the results can be made using the formula above with the constants substituted in. The regression analysis method can be used to interpolate between theoretical data points with information found from computer simulations, or from results from standard fire tests. Bennetts et al (1986) give further information and examples. The fit of the regression lines to experimental results do not fit with as little error as theoretical results due to the approximate nature of the theory of the regression analysis and the variability of the material over the cross section and between tests.

Limitations and conditions on the use of the regression analysis are also covered in NZS 3404, detailing the tests applicable to use, and the limitations of the results.

Eurocode 3 uses a spreadsheet time step formula for predicting the temperature of the protected steel. This equation is similar to the protected steel equation used in this report and stated in Section 2.1.3, except that it includes a term to account for the increase in fire temperature during the time step and adds one third of the heat capacity of the insulation to the steel, rather than one half as is in equation 2.3. The formula is as follows:

$$\Delta T_s = \left(\frac{k_i}{d_i c_s p_s} \right) \left(\frac{H_p}{A} \right) \frac{(T_f - T_s)\Delta t}{1 + \phi/3} - \left(e^{\left(\frac{\phi}{10}\right)} - 1 \right) \Delta T_f \qquad 3.12a$$

where $$\phi = \left(\frac{c_i \rho_i}{c_s \rho_s} \right) d_i \left(\frac{H_p}{A} \right) \qquad 3.12b$$

3.1.6 Determination of PSA from a single test:

PSA is the period of structural adequacy of an element. This can be determined from the results of a single standard fire test provided that conditions a) – d) in Section 3.1.5 are met as well as:

e) The conditions of support are the same as the prototype and the restraints are not less favourable than those of the prototype; and
f) The ratio of the design load for fire to the design capacity of the member is less than or equal to that of the prototype.

These conditions mean that the results from the tests can only be used when the prototype gives equal to or more severe results than those of the member being analysed, particularly in relation to the span of the beam; the load restraints; the support conditions; the section factor and the thickness of the insulation. To obtain results from experimental tests, the member is usually shorter than that of the member in service. This complies with e) above.

No alteration to the results obtained from experimental tests may be made, however, to account for different insulation thickness or steel section factor.

The Eurocode states only once in the document that experimental data may be used to confirm the fire resistance rating of a member. The British Standard, BS 5950:Part 8 gives options to use fire resistance test data to confirm the fire resistance applied to the steel members, giving limitations concerning the applicability of the tests similar to those stated above as listed in NZS 3404.

NZS 3404 also has a clause to cater for circumstances where there is three sided exposure with concrete densities which differ by more than 25 %, or for slabs with a thickness that varies by more than 25 %. This clause makes an allowance for the resulting effect on the steel temperature that these variations make. The effect of different concrete densities and thicknesses are small so a considerably large difference must be present in the construction before the members must be treated as separate cases.

3.1.7 Special Considerations:

A conservative approach is given for designing the fire resistance of connections and web penetrations.

Connections:

NZS 3404 requires that the connections to protected members shall have protection applied with the same thickness as the maximum thickness of the members framing into the connection. This thickness should be maintained over the entire section of the connection including bolt heads, welds and splice plates. This is a conservative approach to the connection.

Connections that transfer design actions from a member requiring a fire resistance rating, and achieve this by satisfying the equations in Section 3.1.4, must satisfy the following conditions:

a) Connection components shall comply with '3.1.4', using the limiting temperature calculated from '3.1.3' and the Section Factor for the exposed cross section of the connection component
b) Connectors shall achieve the same or lower value of (r_f) for the connectors as that for the member being supported, where r_f is defined in '3.1.3'

This is to ensure that the connection meets the fire resistance requirements of the member that it is attached to, ensuring failure of the connection does not occur.

The Eurocode does not give guidelines for the fire resistance rating of connections, but since it gives details on the design of the members, this theory can be transferred to the design of connections.

Beam Web Penetrations

NZS 3404 states

> Unless determined in accordance with a rational fire engineering design, the thickness of fire protection material at and adjacent to web penetrations shall be the greatest of:
> a) That required for the area of beam above the penetration considered as a three sided fire exposure condition;
> b) That required for the area of beam below the penetration considered as a four sided fire exposure condition;
> c) That required for the section as a whole considered as a three sided fire exposure condition

The thickness shall be applied over the full beam depth and shall extend each side of the penetration for a distance at least equal to the beam depth, and not less than 300 mm.

The Eurocode 3 Document and the British Steel code do not have recommendations on the fire resistance of beam web penetrations.

4 CALCULATION OF STEEL TEMPERATURES FOR UNPROTECTED STEEL – ISO FIRE:

4.1 INTRODUCTION:

The temperature rise of unprotected steel can be modelled using a variety of computer programmes and calculation methods. In the New Zealand code, formulas provide an estimate of the time until a limiting temperature is reached, which is sufficient for situations where a designer is confirming the structural stability of a steel member. These formulas however are valid for a limited time period, temperature range and for a limited range of steel member sizes. They also only provide an estimate of the time at which a member will reach a particular temperature, based on test results from experiments performed with unprotected beams exposed to the standard fire.

The spreadsheet method is a simple calculation method which estimates the temperature in a one dimensional heat flow or 'lumped mass' approach. It was developed using basic heat transfer principles and the amount of temperature rise of the steel is based on the energy being transmitted to the member. The major variable to influence the rate of temperature rise of unprotected steel beams when using the spreadsheet method is the H_p/A value, which is a ratio of exposed perimeter to cross sectional area, and the inverse of the average or effective thickness. This is discussed further in Section 1.6.3.

In this section, the computer programmes SAFIR, Firecalc, and FIRES-T2 are compared, to examine the repetitivity of these finite element software programmes, and to determine whether the most user friendly, SAFIR, could be used in place of the others with the same accuracy of results. The results from SAFIR are also compared with the results from the spreadsheet method to examine the accuracy of the spreadsheet method. It is also investigated whether the spreadsheet method can be used with the same confidence as with the finite element computer programmes for simple fire related steel member problems such as the average temperature of the steel after a given time.

Three beam sizes have been considered here to determine if the methods discussed are applicable for a range of sizes. The geometry of these beams are sized according to Australian universal beams from BHP Steel, (1998). Unprotected beams subjected to four sided exposure have been examined, followed by three sided exposure with and without a concrete slab on top of the beam.

4.1.1 Assumptions

The assumptions made when estimating the temperature of the steel beams exposed to fire by the spreadsheet method are that the steel has a uniform temperature distribution across its cross section and that the cross section is uniform along the length of the beam. The beam is exposed to a standard fire and the temperature of the air immediately adjacent to the beam is assumed to be that of the standard fire at the particular time. The spreadsheet method assumes a constant thickness of the steel, which is based on the H_p/A value.

The emissivity of the flame has been taken as 0.50 as suggested by Purkiss, Drysdale, and the convective heat transfer co-efficient is 25 W/mK in the spreadsheet analysis as well as the in the SAFIR simulations. For the comparison with the FIRE-T2 computer programme the heat transfer coefficient constants are not known.

For the purposes of this report the properties of the steel are generally assumed to remain constant with temperature which is slightly inaccurate. Purkiss, (1996) recommends no variation of steel density with temperature and that this value remain at a constant value of 7850 kg/m^3. Ting, (1999) looked at the discrepancies that arise by assuming constant values for specific heat of steel, and found that for time equivalence results, the variation is less than 10%. A comparison of the results found from SAFIR, with results from the spreadsheet method with varying specific heat has been made to confirm the influence of the variation of the properties of steel. See Section 1.6.2 for details of the variation of steel properties with temperature.

4.1.2 Analysis Between Methods of Temperature Evaluation:

When looking at the comparisons between different methods of analysing temperatures of the steel, it must be established what is conservative and what is non conservative.

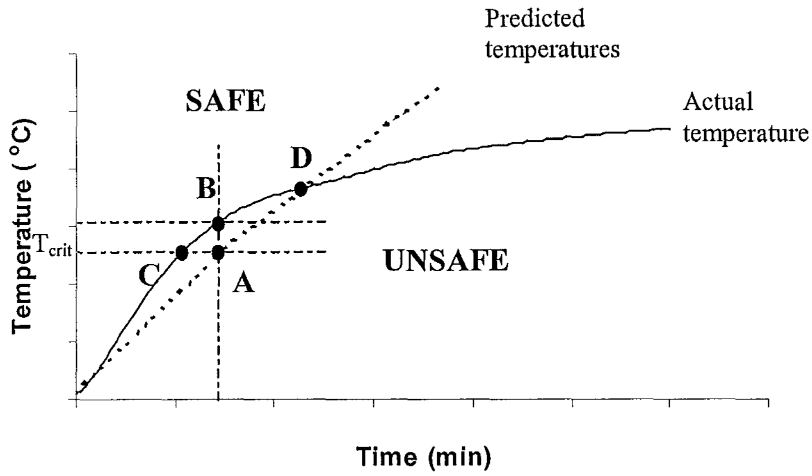


Figure 4.1: Schematic graph showing the comparisons made between approximate formulas and time temperature curves

If the formula is used to calculate the temperature, at a certain time, the formula predicts a temperature that is too low, ie. from Figure 4.1, the formula will predict a temperature at the point A, whereas the actual time temperature curve gives a higher temperature relative to point B. This is unsafe because a member which can carry a certain load at temperature A could fail at temperature B.

If the formula is used to calculate the time that a limiting temperature is reached, the formula is again unsafe. The actual fire curve gives a time as seen in Figure Figure 4.1 at C, while the formula gives a time located at point A. Since point C occurs at a earlier time than point A, the formula gives a fire resistance rating time for the element which is longer than it actually is safe for.

Graphically, if the line is below the curve, as from the origin to point D, then the formula is giving unsafe or non conservative results. If the line is above the graph as from point D to the end of the line, the formula is giving conservative and safe results.

4.2 RESULTS FOR FOUR SIDED EXPOSURE:

A comparison of three methods of thermal analysis of unprotected steel beams is made in this section. The results from SAFIR are deemed to be the most accurate method of analysis due to studies with experimental data showing good correlation with the results from SAFIR (Gilvery and Dexter, 1997). The results from the spreadsheet programme have been calculated with a 60 second time step, and the method and equations used for the estimation of the temperatures are found in Section 2.1.2. The linear equations found in the New Zealand and Australian codes and ECCS recommendations are outlined in Section 0 and have been used with the appropriate H_p/A value for four sided exposure.

With four sided exposure to the ISO fire, the steel member generally has a close to constant temperature over the cross section of the beam. There are only small temperature variations over the cross section due to the steel geometry and the temperature profile is symmetrical.

4.2.1 Results from a simulation with the SAFIR programme:

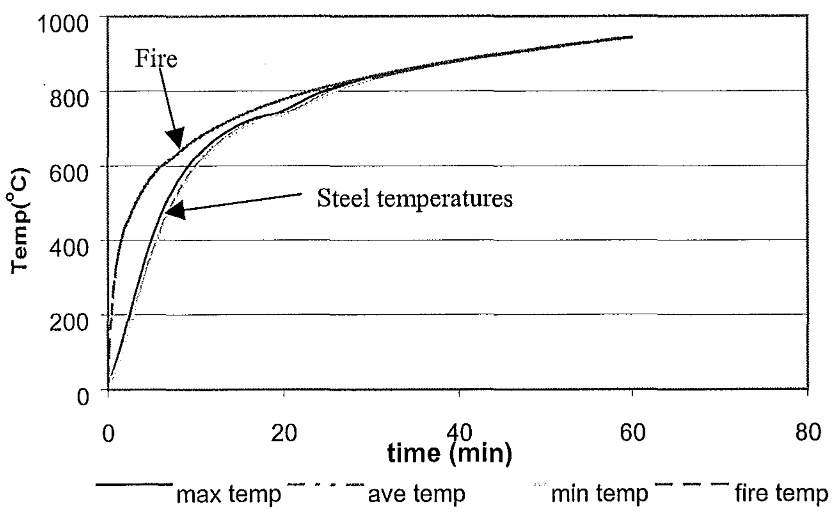


Figure 4.2: Time temperature curve from a SAFIR simulation showing the variation of temperature of different elements in the beam for four sided exposure to an ISO fire for the 530UB82.0 beam

Figure 4.2 shows the variation of temperature between the different points on the cross section of the beam. The maximum and minimum temperatures shown in the graph are the maximum and minimum temperatures of an element at each time step over the time period examined here. The element in which the maximum or minimum temperature is found is not necessarily the same throughout the entire time period of the graph. During the later stages of the simulation, however, the same element in the cross section has the maximum and minimum temperatures. The average temperature on the curve is simply an average of all elements at each time step. No consideration due to the size or position of the element on the cross section has be made. In the later stages of the test this is especially acceptable because these temperatures of all the elements merge to within a small temperature range, and the later temperatures are more vital when considering the structural behaviour of the beam.

In each of the SAFIR curves there is a small plateau region in the temperature of the steel, when the beam has been subjected to the fire for around 20 minutes. This reduction in the rate of temperature rise is due to the increase in specific heat of steel, which occurs when the temperature of steel is between 650 °C and 800 °C. The same behaviour and similarities are present in all three sizes of beams tested.

The specific heat changing has an impact on the rate of temperature increase because it governs the amount of energy that is required to be absorbed by the steel for its temperature to be raised. The value of the specific heat of steel changes from being between 600 – 800 J/kg K at temperatures below 650 °C, to a maximum of 5000 J/kg K when the steel reaches a temperature of 735 °C as shown in Figure 1.1. This variation in magnitude of about 8 causes the significant flattening of the curves.

The maximum, minimum and average temperatures of elements in the SAFIR tests are shown in Figure 4.2. The maximum difference between the maximum and minimum temperatures is 49 °C, which occurs 5 minutes after the start of the simulation when the temperature range is 353 to 402 °C, and the average temperature is 360 °C. This results in the maximum temperature being 14 % higher than the minimum temperature and 12 % higher than the average.

The maximum temperature at this time is located at the element in the middle of the length of the web and the minimum temperatures at this stage are located midway along overhang of the flange from the web-flange intersection as shown in Figure 4.3:

The central element of the web is the hottest region due to the width of the web being only 4.5 mm compared with the width of the flange being 7.0 mm. Since the web is relatively long in comparison with the length of half the flange width, the neighbouring elements of the web are also hotter and heat is conducted through to the central element of the web from both sides giving it the highest temperature.

The mid section of the flange is the coolest area by the same theory. It has a thicker width, and very little heat is conducted into the element because the whole of the flange is of similar temperature. The middle section is the coolest because the ends are subjected to fire on three sides and are therefore at a cooler temperature, and where the web meets the flange there is conduction from the hotter web sections increasing the temperature. The elements of the flange and web vary only slightly in temperature but the difference between the flange and the web can be quite significant during some stages of the fire test.

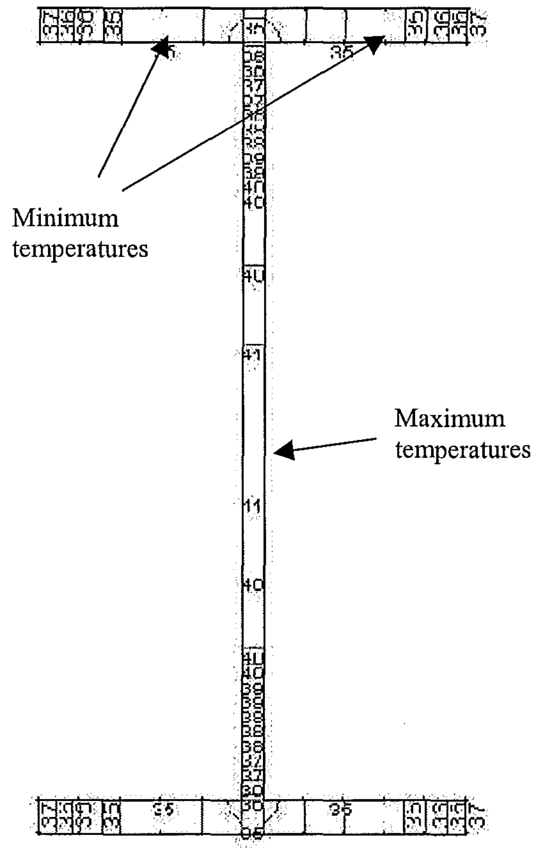
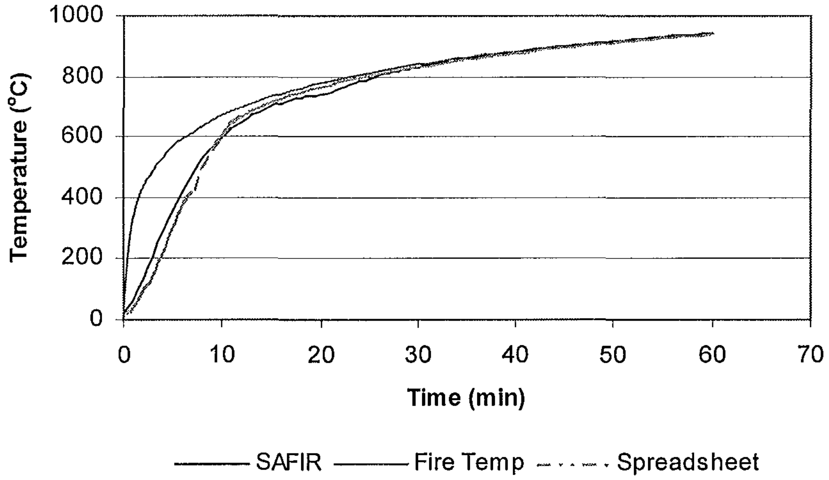
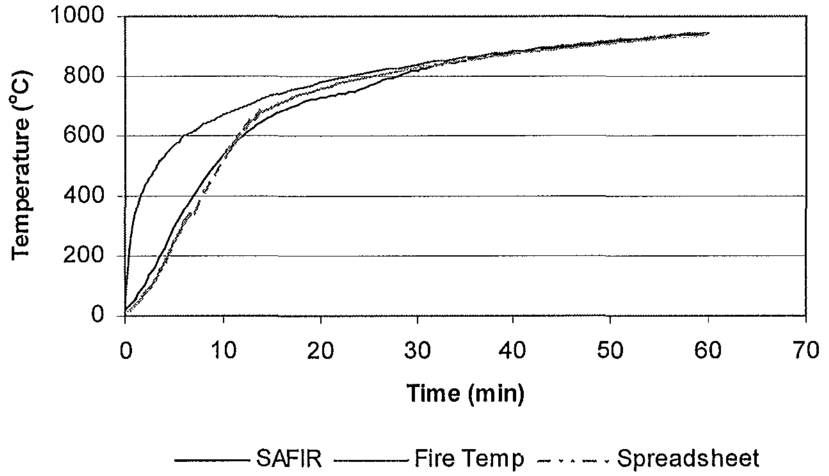


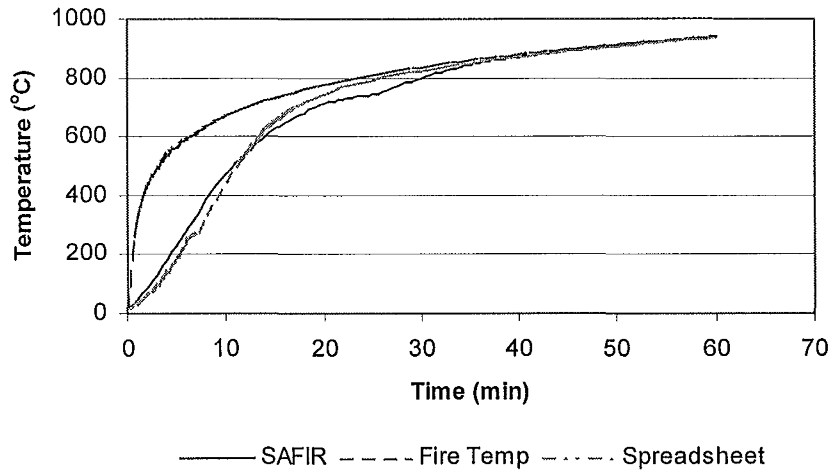
Figure 4.3: Temperature contour lines showing the temperature profile and where the maximum and minimum temperatures are located over the cross section of the steel section

4.2.2 Unprotected steel beam with four sided exposure:

Unprotected steel beams exposed to fire on four sides have been simulated in SAFIR and the temperatures calculated with the spreadsheet method. Figures 4.4 a-c show the thermal response of unprotected steel beams exposed to the standard ISO 834 fire on all four sides. The temperature of the steel increases as the temperature of the fire increases, until the steel temperature is practically the same as that of the fire. The graphs show the time-temperature profile of three different sized beams, from calculations with the spreadsheet method, see Section 2.1.2, and from simulations performed in SAFIR, see Section 2.3.1.







Figures 4.4 a-c: Comparison between the results from SAFIR and the spreadsheet method for unprotected steel beams with four sided exposure to the ISO standard fire. From top to bottom beam sizes a. 180 UB 16.1, b. 310 UB 40.4 and c. 530 UB 82.0

For all three sizes of beam, the spreadsheet method of calculating the temperature of an unprotected beam over time correlates well to the results given from the SAFIR programme. The temperatures from the spreadsheet method are lower than the average temperatures over the beam as exported from the SAFIR programme for approximately the first 10 minutes. After this time the spreadsheet results are slightly higher than the SAFIR results until they merge to be within 2 °C of each other. At temperatures of over 800 °C, this is an error of within 0.25 %.

Differences between the spreadsheet and SAFIR programme can be accounted for by considering the different methods of evaluation of temperature. The spreadsheet uses constant values for thermal conductivity, density and specific heat for steel and protection when used. The SAFIR programme uses more accurate graphs of these properties varying with temperature. The spreadsheet method does not consider variances in temperature over the cross section but assumes a constant temperature instead.

4.2.3 Comparison with NZS 3404 and ECCS formulas for four sided exposure:

The New Zealand and Australian codes contain formulas to give an estimate of the temperature of four and three sided fire exposed steel beams. These formulas are based on results from experimental standard fire tests performed by the British Steel Institute. The ECCS recommendations are also formulated empirically and have been compared with experimental data in ECCS, (1985).

The formulas existing in the codes are:

$$t = -4.7 + 0.0263T_l + 1.67T_l \, {}^{A}\!/_{H_p} \qquad 4.1$$

from NZS 3404 and AS 4100

This formula is valid in the temperature range of 500 °C to 850 °C by the New Zealand code, but the Australian code has an upper temperature limit of the steel as 750 °C. Below 500 °C, both codes allow linear interpolation between the time that the steel becomes 500 °C and a temperature of the steel of 20 °C at the start of the test. This formula has a limit for the size of the steel beams, based on its Section Factor, with the H_p/A value between 15 and 275 m^{-1}.

ECCS, (1985) recommend using:

$$t = 0.54(T_l - 50)\left(A/H_p \right)^{0.6} \qquad 4.2$$

ECCS limits this formula to the steel temperature range of 400 °C and 600 °C. The time when these temperatures may occur are limited by the time period of between 10 and 80 minutes, and the formula is valid for members with a section factor, H_p/A, value of between 10 and 300 m^{-1}.The lightest beam used in this report, 180 UB 16.1 has a section factor, which is out of the recommended size range for these equations.

Figure 4.5 a-c show the accuracy of the formulas provided in NZS 3404 and AS 4100; and recommended by the ECCS for four sided exposure to unprotected steel beams. The range for both has been extended beyond that which is recommended by the committees formulating the formulas, but as can be seen the lines generally fit within the same accuracy of the recommended range for a much larger temperature spread and longer time period than those suggested. The time temperature curve to which these equations are being compared to is calculated using the spreadsheet method, which is considered to be an accurate account of the true behaviour of a steel member in a standard ISO 834 fire test.

From Figure 4.5 a-c, the formula range for the ECCS formula, Equation 4.2, can be extended to at least 700 °C as an upper limit. This could even be extended to 800 °C as this temperature is within the same accuracy from the spreadsheet curve as temperatures that are in the recommended range. Below 400 °C, linear interpolation method could be recommended as this will gives conservative or shorter values for the times that a temperature is reached. The temperature range suggested by for the New Zealand code equations appears valid, with an upper temperature limit of 850 °C, and linear interpolation for temperatures below 500 °C.

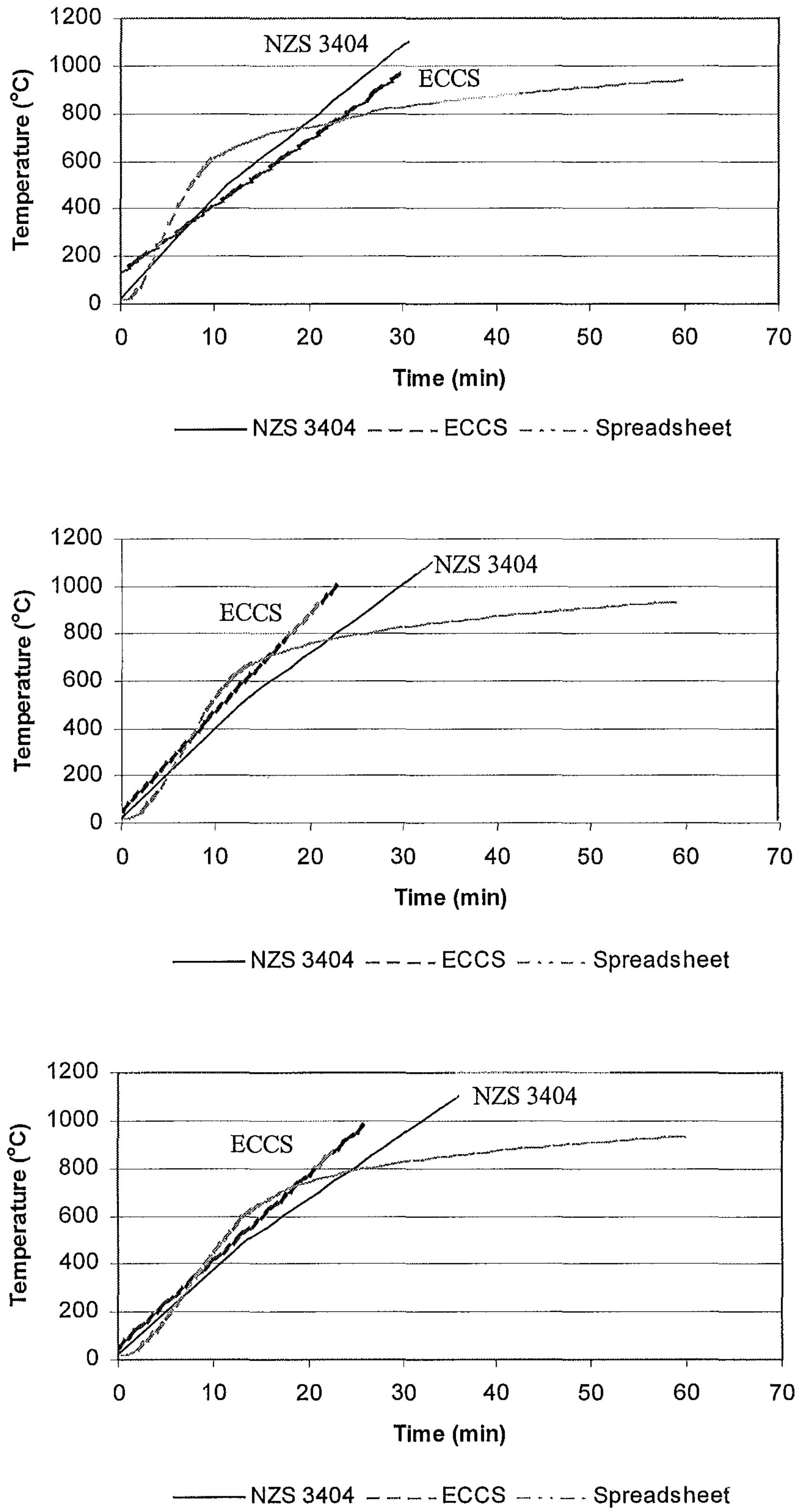


Figure 4.5 a-c: Comparison of the linear equations provided by NZS 3404 and ECCS with the temperatures obtained from the spreadsheet method with four sided exposure to an ISO 834 fire for (a). 180 UB 16, (b). 310 UB 40.4 and (c).530 UB 82.0

Equation 4.1 from NZS 3404 is much less conservative as it gives temperatures that are lower than Equation 4.2 from ECCS, and deviates from the spreadsheet curve more throughout the temperature range than the ECCS formula does. The accuracy of the spreadsheet, therefore, is important to show the accuracy of the equations. From Section 4.2.2, the spreadsheet gives very close results to those found from the SAFIR programme, which itself has been proven to model the thermal response of a steel section from comparison with experimental data, (Gilvery and Dexter 1996).

The largest deviation from the spreadsheet curve occurs when the steel is reaching the limiting temperature range of between 550 – 800 °C. The equations generally overestimate the times it takes for these temperatures to be reached which is unsafe, see Section 4.1.2.

For example, if an unprotected 310 UB 40.4 beam was being considered for the rate of temperature increase, equation 4.1 from NZS 3404, gives a time of nearly 16 minutes until a temperature of 600 °C is reached, and equation 4.2 from ECCS, suggests a time of just over 13 minutes. According to the spreadsheet calculations, however, the temperature will reach 600 °C in around 11.5 minutes. Although these times are not substantially different, they are non-conservative compared with the spreadsheet temperature curve. The ECCS formula generally gives times that are closer to the spreadsheet curve than the New Zealand Code equations are.

The differences between the spreadsheet results and the formulae are relatively constant for the different sizes of the beams, when the beam sizes are within the recommended range for the formula. From Figure 4.5 a however, the formulas are significantly further from the spreadsheet temperature curve than as seen in Figure 4.5 b and c. The section factor for the 180 UB 16.1 beam for four sided exposure is 334 m^{-1} which is outside of the section factor range recommended by both ECCS and the NZS 3404/AS 4100 standards. Both lines from the formulas are a significant way from the spreadsheet curve in this case, so it appears that the steel section size limitations of the formulas are valid.

The ECCS equation has a time period limitation during which the equation is valid. This does not appear to be necessary as the lines resulting from this formula fit to the spreadsheet curve for a longer time period than that suggested.

For the NZS 3404 equations, the limitations imposed on the equations currently are logical and fit well with the data. The ECCS equations give limitations that are too conservative and can be extended. The upper temperature limit should be extended to 750 °C instead of 600 °C and linear interpolation should be recommended for temperatures below 400 °C. The limitations on the section factor appear necessary as Figure 4.5 a shows, but the time limitations do not seem necessary at all.

4.3 RESULTS FOR THREE SIDED EXPOSURE:

Three sided exposure usually occurs for unprotected steel beams when the beam is supporting a concrete floor slab on its top flange. It can also occur if there is another material protecting the top flange such as insulation between supported purlins, so two cases are considered in this chapter. SAFIR 1 results are results found from simulations in SAFIR without a concrete slab on the top flange, but with no fire exposure on the top face of the top flange, modelling an insulation effect. SAFIR 2 has a concrete slab resting on the top flange, providing the beam with protection against the fire and thus making three sided exposure.

The concrete slab used in these simulations is a 150 mm thick slab of calcareous based concrete with properties from Eurocode 2, with aggregate material primarily of limestone. The thickened lines around the beam in Figure 4.6 indicate the contour that is exposed to the ISO 834 fire in the simulations.

The layout for the SAFIR 2 simulation is shown in Figure 4.6:

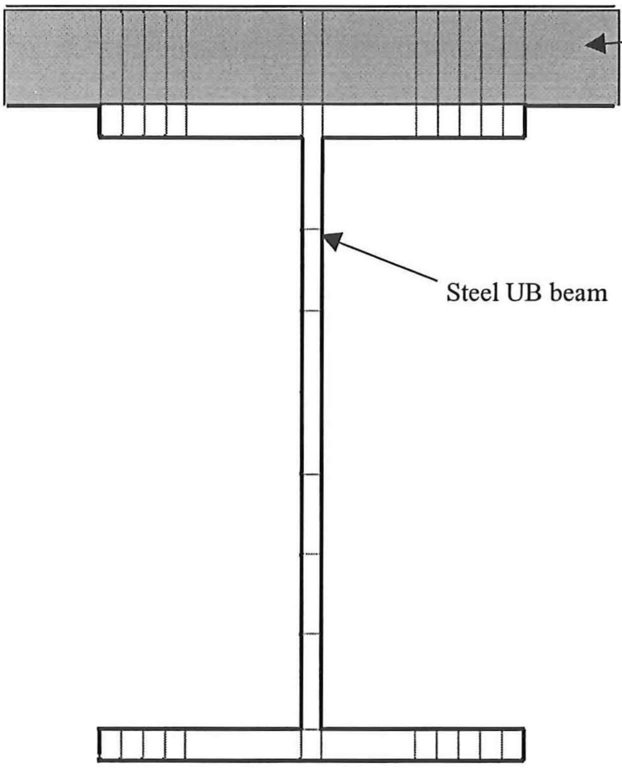


Figure 4.6: Layout of three sided exposure with a concrete slab

The results for three sided exposure to an ISO 834 fire differ from those of four sided exposure. The SAFIR results have a greater temperature spread between the maximum and minimum values for different elements due to cooler steel temperatures at the unexposed face. The option of simulating three sided exposure with or without a slab present gives more variation to the results found.

With three sided exposure to the fire, the steel section has a temperature gradient across the cross section. With a concrete slab in place, the variation is greater across the section during to the cooling effects of the slab. The average temperature is assumed to be the average of all elements from the SAFIR simulation, which is acceptable for a thermal analysis, and best for a comparison with the spreadsheet method. However, if a structural review of the member was being made, the temperatures at vital points of the section such as the temperature of the lower flange should be considered.

4.3.1 Results from simulations with the SAFIR programme:

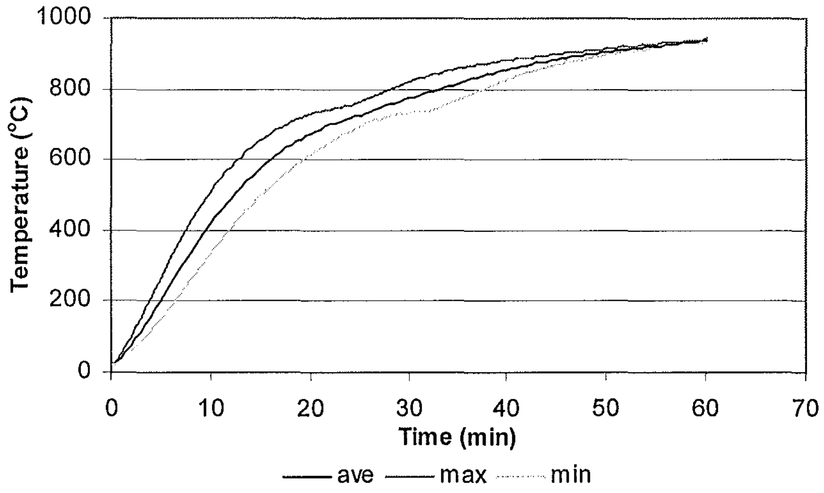


Figure 4.7: Maximum, average and minimum temperatures found from the SAFIR 1 results of a simulation of a 530 UB 82.0 beam exposed to the ISO 834 fire on 3 sides, (no slab).

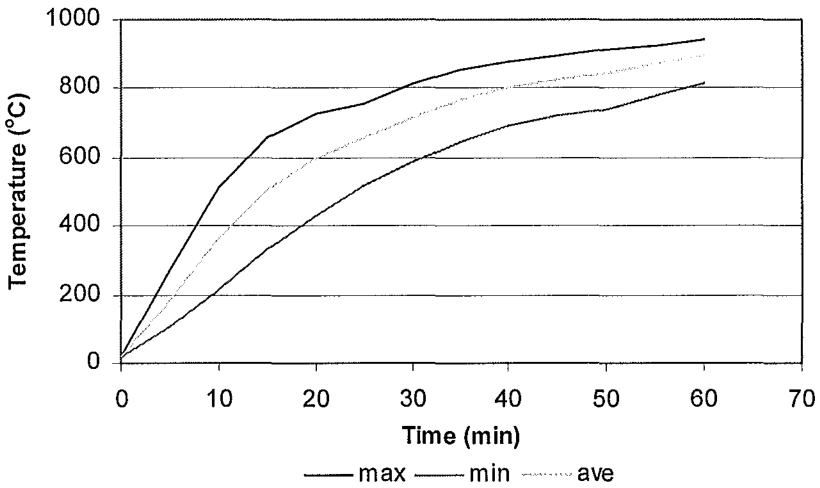


Figure 4.8: Maximum, average and minimum temperatures found from the SAFIR 2 results of a simulation of a 530 UB 82.0 beam exposed to the ISO 834 fire on 3 sides with a 150 mm slab on the top flange.

Figure 4.8 shows a much larger spread in maximum and minimum temperatures for three sided exposure with a concrete slab in place than Figure 4.7 which does not have a slab. The temperatures in Figure 4.7 merge to within 10 °C at the end of the simulation, which is around a 1 % difference in results when the temperatures are over 900 °C. The maximum difference in the results from Figure 4.7 is 179 °C, which occurs after 10 minutes. At this time the temperature range is from 353 to 532 °C

The results found from the SAFIR simulation with the slab continually has a large deviation between the maximum and minimum temperatures and although this reduces towards the end of the test, the difference is still 124 °C after 60 minutes. The maximum difference in temperature of the elements is 326 °C, which occurs after 15 minutes and when the temperature range is 329 to 655 °C. Although the curves in Figure 4.8 appear likely to get close to converge, from the limited time scale used in these simulations there is no clear defined temperature that the member is heading towards.

As expected the maximum and minimum temperatures are located as shown below in Figure 4.9:

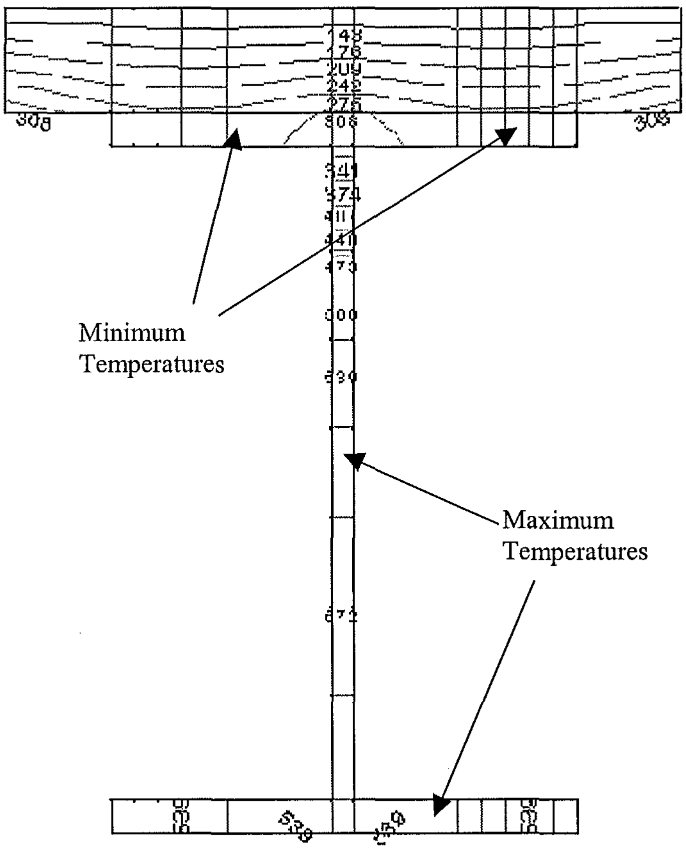


Figure 4.9: Location of maximum and minimum steel temperatures on the cross section of a beam for three sided exposure as found from simulations with and with a slab on top of the beam.

From Figure 4.5 a-c, the formula range for the ECCS formula, Equation 4.2, can be extended to at least 700 °C as an upper limit. This could even be extended to 800 °C as this temperature is within the same accuracy as in the recommended range. Below 400 °C, a linear interpolation method could be recommended as this will give temperatures close to the spreadsheet curve. The temperature range suggested by for the New Zealand code equations appears valid, with an upper temperature limit of 850 °C, and linear interpolation for temperatures below 500 °C.

Although the temperature gradients differ markedly between the two simulation types, this only occurs due to the minimum temperature being much lower in the SAFIR 2 simulations from the effects of the concrete slab. The maximum time-temperature curves in both simulations are the same, meaning that the maximum temperatures are not affected by the presence of a concrete slab on the top flange. This is intuitively correct, because the maximum temperatures in the SAFIR 2 simulations are found in the bottom flange and web which are exposed to the fire and not in contact with the slab.

Although the cooling effects do cool the top flange and the top of the web, the temperature is quite constant throughout the rest of the cross section giving the same maximum temperatures in SAFIR 1 and SAFIR 2. The effects of conduction do not change the temperature across the section below the top of the web.

These maximum temperatures are also the same as the maximum temperatures found in the four sided ISO 834 fire exposure to unprotected steel, as seen in Section 4.2.1. When the curves are plotted on the same graph, the curves are exactly the same as seen in Figure 4.mm below. Although it is hard to distinguish, there are three curves plotted in Figure 4.10, showing the maximum temperatures found in four sided exposure, three sided without a slab (SAFIR 1) and three sided with a slab (SAFIR 2). The maximum temperatures found in the bottom flange and web of the beam is therefore independent of the presence of a slab, and if the maximum temperature over the cross section is required to be found, then from Sections 4.2.1 and 0, the spreadsheet method gives an accurate answer with the least difficulty.

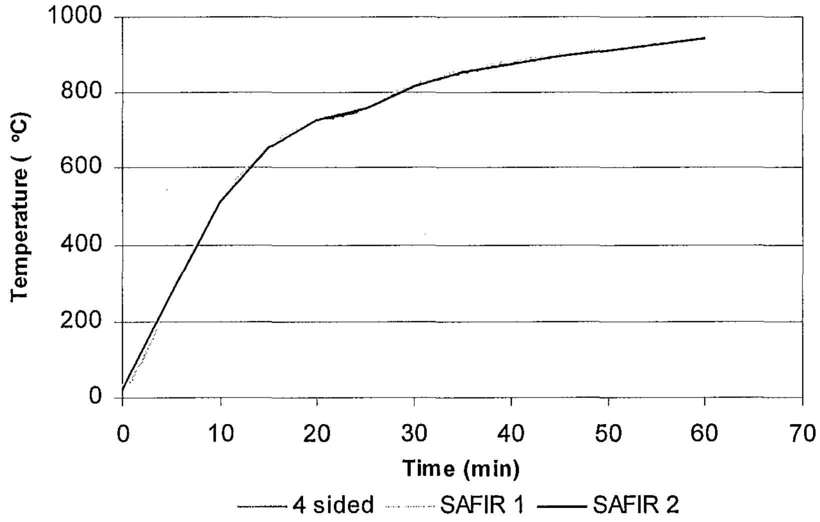


Figure 4.10: Maximum temperatures from simulations in SAFIR of four sided exposure, and three sided with and without a slab.

4.3.2 Unprotected steel beam with three sided exposure:

The spreadsheet method for three sided exposure is the same as with the four sided exposure with a modified H_p/A value due to a smaller perimeter of the beam exposed to the fire, but with the same cross sectional area of the steel section.

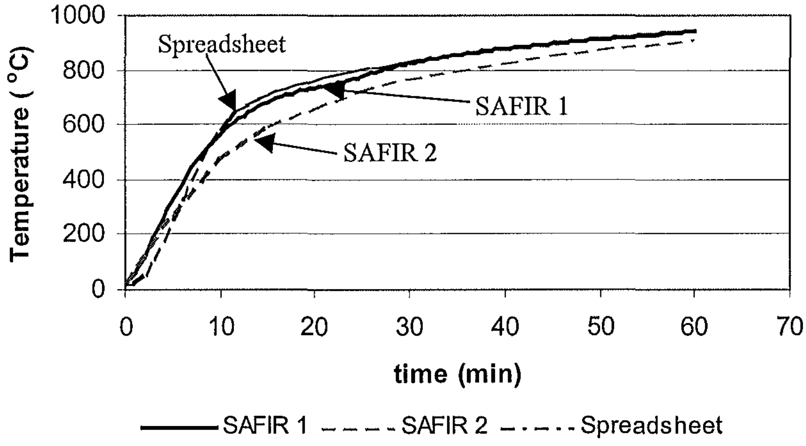
The SAFIR programme was also used with the same procedure as with four sided exposure with two variations. For the comparison of three sided exposure of unprotected steel, a simulation has been performed in SAFIR with the beam being exposed on three sides to the ISO fire, with the fourth, top flange kept unexposed.

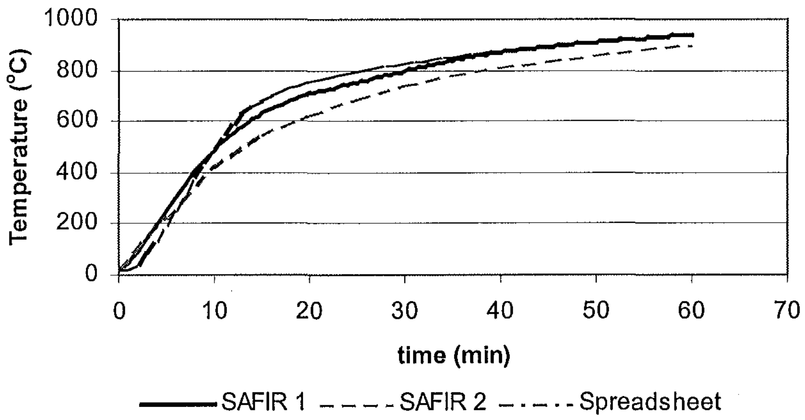
Usually when a beam is exposed on three sides however, a concrete slab is present, protecting the beam on the fourth side, so simulations in SAFIR have been made with this construction. For simplicity in discussing the two different SAFIR simulations, and as in Section 4.3.1, the following notation has been adopted:

SAFIR 1 – three sided exposure without concrete slab

SAFIR 2 – three sided exposure with a 150 mm concrete slab.

The temperatures here are again the simple average of all elements in the beam cross section, for simplicity for comparisons with the spreadsheet method.





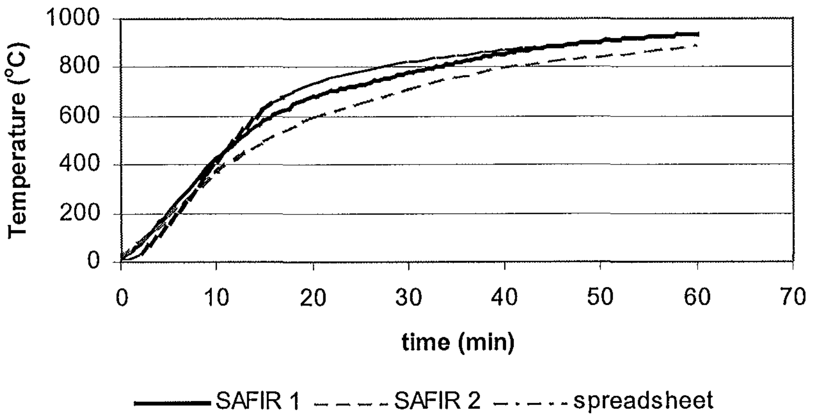


Figure 4.11a-c: Comparison of results from SAFIR and the spreadsheet method for an unprotected steel member subjected to three sided exposure of the ISO 834 fire from top to bottom a. 180 UB 16.1, b. 310 UB 40.4, c. 530 UB 82.0

From Figure 4.11 a-c, the spreadsheet curve is close to the SAFIR 1 curve without a concrete slab protecting and cooling the top flange of the steel beam. This is because the spreadsheet method as used in this report makes no allowance for the effect of a concrete slab absorbing heat. The spreadsheet assumes that all heat transferred to the steel section is absorbed by the section and all energy absorbed in turn contributes to the temperature rise of the member.

Differences between the spreadsheet method and SAFIR 1 result from the spreadsheet assuming a constant thickness over the cross section of the beam, while SAFIR accounts for the true thickness and allows conduction across the beam. The effective thickness of the section as used in the spreadsheet method is increased with three sided exposure due to a decreased section factor as the heated perimeter decreases, see Section 1.6.3. The conduction feature in SAFIR means that although the beam is not heated on the top face of the top flange in the SAFIR 1 simulation, there are no outside influences to stop it rising in temperature. The SAFIR 2 simulation has concrete protection on the top flange so that although it does heat up, a significant amount of the energy transferred to the top flange is then conducted to the concrete slab.

Using the spreadsheet results is a conservative method of predicting the temperature of three sided fire exposure, since the temperatures that this method predicts are higher than other methods. Since in most 'real' cases of three sided exposure to fire, a slab would be present, the spreadsheet method is possibly too conservative for the average temperature. A reduction in the formula of the heat transferred to the beam could be an alternative method of estimating the likely temperatures that would be reached in a fire. By considering the average temperature in the slab at each time step, an energy balance could be found to account for the heat and energy loss to the slab, resulting in a more accurate estimation of the likely temperatures reached in the steel section.

The SAFIR 2 simulation with the concrete slab resting on the top flange is at a significantly lower temperature throughout the test run. The difference in temperature between the two SAFIR results is the effect of the addition of a concrete slab, which lowers the temperature of the top flange and therefore the average temperature of the beam, because heat is conducted from the beam and absorbed by the concrete. This causes a large variation between the maximum and minimum temperatures of the beam as can be seen in Section 4.3.1 and in Figure 4.7 and Figure 4.8.

4.3.3 Comparison with NZS 3404 and ECCS formulas for three sided exposure:

The New Zealand Steel Code has a different equation for three sided exposure, from that for four sided exposure as stated in Section 4.2.3. This is in the form below:

$$t = -5.2 + 0.0221T_l + 3.40T_l \frac{A}{H_p} \tag{4.3}$$

The temperature range and limitations on the cross section of the member are the same as described in Section 4.2.3 for equation 4.1, as stated below:
Equation 4.3 is valid in the temperature range of 500 °C to 850 °C by the New Zealand code, and up to 750 °C for the Australian code. Below 500 °C, linear interpolation is used between the time that the steel becomes 500 °C and a temperature of the steel of 20 °C at the start of the test. The beams size limitations are based on its Section Factor, with the H_p/A value between 15 and 275 m^{-1}.

The ECCS recommendations use the same formula as with four sided exposure, equation 4.2, but with an altered H_p/A value to allow for three sided exposure to the fire. This formula is:

$$t = 0.54(T_l - 50)\left(A/H_p \right)^{0.6}$$

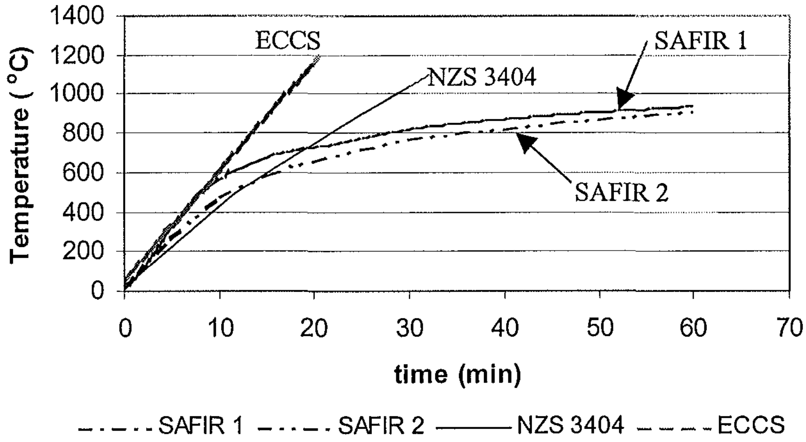
with temperature limitations of 400 °C to 600 °C, time of between 10 and 80 minutes, and is valid for beam sizes with a section factor, H_p/A, value of between 10 and 300 m^{-1}.

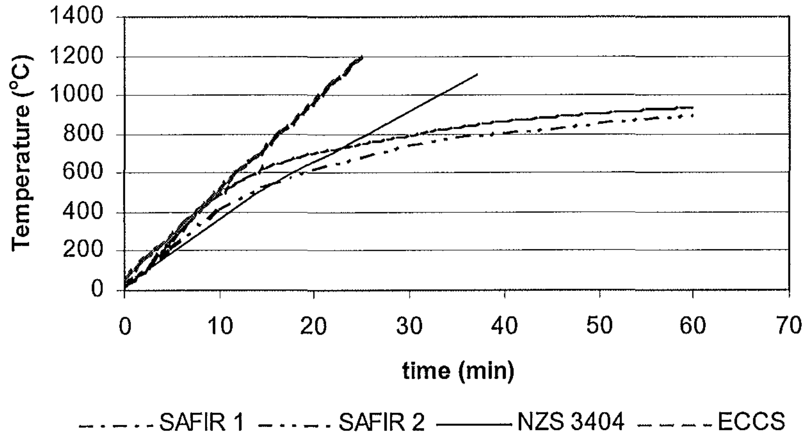
In Figure 4.12 a-c the curves that the two straight-line equations are compared with are both from SAFIR, namely SAFIR 1 and SAFIR 2 as used earlier in Section 4.3.

The SAFIR curves are the result of simulations with ISO 834 fire exposure to three sides of the cross section, with and without a 150 mm concrete slab resting on top. The addition of the slab lowers the of steel temperatures estimation because not only does it protect the top face of the beam from fire, but it also absorbs heat with its high thermal mass and subsequently cools the steel beam.

The equations show consistency with the two curves in Figure 4.12 a-c. Equation 4.3, provided in NZS 3404 and AS 4100, fits closely to the SAFIR 2 time-temperature curve with the concrete slab. Comparing the line given by equation 4.3 with the curve from the SAFIR 1 simulation, however, gives predictions that are too low and unsafe, see Section 4.1.2. Since most three sided situations would occur with a slab present, using equation 4.3 to predict the average steel temperatures for three sided exposure appears to be more realistic. This formula is based on regression analyses based on British temperature data and a more substantial modification is made from the four sided exposure formulas than those that is recommended from ECCS (1985) committee.

The ECCS line, which results from equation 4.2 with a lowered H_p/A value, agrees well with the results from the SAFIR 2 simulation in the temperature range recommended. When using equation 4.2 to calculate the temperature of the beam at elevated temperatures for three sided exposure to fire the only change made to the calculation is the section factor, or effective width. As can be seen in Figures 4.4 and Figure 4.11, the SAFIR results are close to that calculated from the spreadsheet method, in which the variation between four and three sided exposure is also only a change in section factor. This all means that the ECCS equation fits best with the SAFIR 1 curve because it fits well with the SAFIR curve for four sided exposure and the same principles and assumptions are used with the SAFIR 1 curve but not the SAFIR 2 curve due to the concrete slab in the latter simulation.





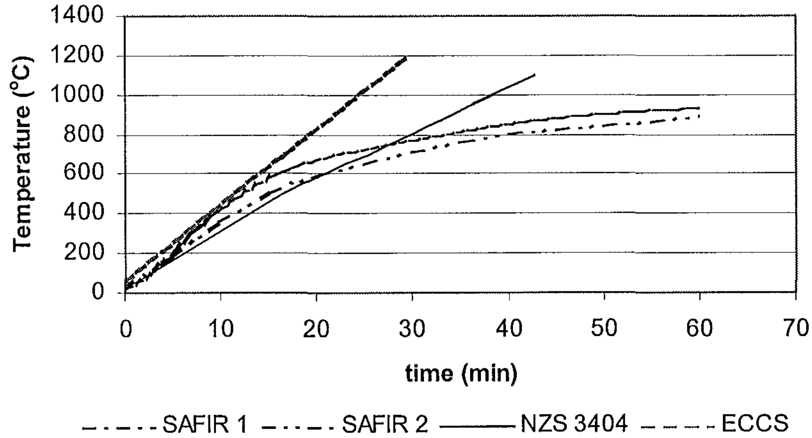


Figure 4.12 a-c: Comparison of the linear equations provided by NZS 3404 and ECCS with the temperatures obtained from SAFIR with three sided exposure to an ISO 834 fire for a. 180 UB 16, b. 310 UB 40.4 and c.530 UB 82.0

The temperature range that equation 4.3 is valid for is non conservative, when comparing the line with the time temperature curve from SAFIR 1. Neglecting the results from Figure 4.12 a, due to the section factor for this beam size being out of range, the upper limit for the temperature based on the results of Figure 4.12 b and c, should be closer to 750 °C than the present 850 °C in the New Zealand Steel Code. This is the upper temperature limit in the Australian Code. The ECCS equation temperature limitations could be modified, by increasing the upper limit, but by a lesser amount than suggested for four sided exposure in Section 0. The temperature range for equation 4.2 could be raised to at least 700 °C for three sided exposure, with a linear interpolation region added to the method here for temperatures below 400 °C.

Since the formula for equation 4.3 is modified for three sided exposure from equation 4.1, the line from equation 4.3 fits better with the SAFIR 2 curve with a slab. This is because the data that the line is formulated to fit to is from results of three sided exposure with a slab present, from British Steel Institute tests, SNZ, (1997).

Equation 4.3, therefore, appears to give a more realistic prediction of the average temperature of steel beams with three sided exposure, but again equation 4.2 is more conservative, by giving higher temperatures. The designer may wish to choose a more economical design by using the estimations of the NZS formulas, but the factor of safety in design is less than when using alternative methods of temperature estimation.

Although the average temperature of steel beams is best predicted by equation 4.3, the ECCS formula, equation 4.2, gives a temperature estimation closer to the maximum likely temperature that will be reached in the steel, which is unaffected by fire exposure conditions, see Section Figure 4.10. Using the maximum temperature instead of the average temperature for three sided exposure is more conservative, as it gives higher temperatures and will give a more likely failure time for simply supported members. The temperature of the steel section is significantly decreased from a cooler top flange, while the maximum temperatures found in the lower flange and web are not affected by the presence of a concrete slab. This means that the presence of the concrete slab will not change the failure temperature of the lower flange and therefore not change the failure temperature of the member.

It is therefore recommended that one equation is used to estimate the limiting temperature of a steel member and that the four sided section factor is used in the equation. The ECCS formula, equation 4.2, gives the best correlation to the maximum temperature in the member from the results seen in Section 0.

4.4 COMPARISONS WITH OTHER FINITE ELEMENT PROGRAMMES:

4.4.1 Comparison of FIRES-T2 with SAFIR:

FIRES-T2 is a computer programme that evaluates the temperature history of two dimensional structures in fire environments. The solutions are found through finite element modelling coupled with time step integration. The same heat transfer principles are applied to the formulations made in FIRES-T2 as in SAFIR so the results should be similar.

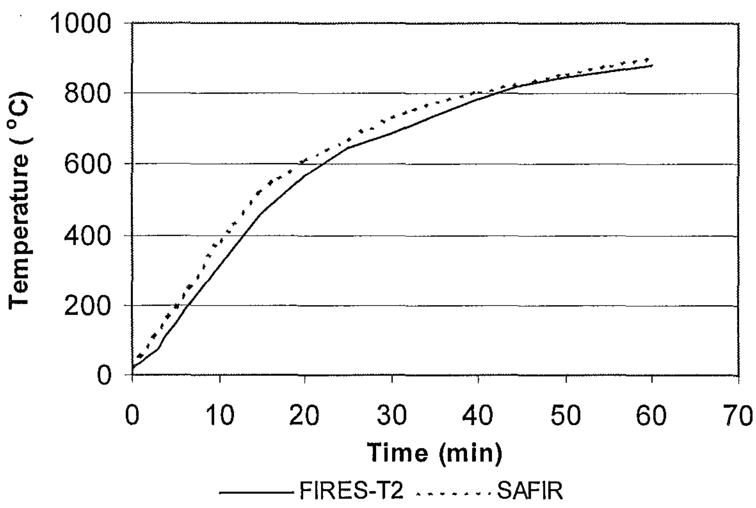


Figure 4.13: Comparison between the results from the SAFIR programme with temperature results from FIRES-T2 for the unprotected 530 UB 82.0 beam with three sided exposure and a concrete slab on the top flange

Figure 4.13 shows that using the same heat transfer techniques in a computer model gives very similar results. The beam that the simulation of FIRES-T2 was performed on was a section from the British Steel Sections Product Brochure, and is close to the size of the BHP 530 UB 82.0 used throughout this report. The two beams have close to exactly the same dimensions of each other with rounding, and the largest difference in dimension is the root radius. Both beams have been subjected to the ISO 834 fire with three sided exposure.

Differences in these two curves could be the result of different sized elements in the finite element modelling system and nodal points could be located at different places around the beam cross section. The two curves show the average temperature of the provided locations of the beam. The averaging system in place here has been a simple mean of all temperatures at each time step, but a weighted mean with regards to the area of the beam cross section at that temperature may provide slightly more accurate or consistent results between the two programmes.

The mechanical properties of steel, concrete and insulation, namely density, specific heat and thermal conductivity vary with time in both computer programmes. There are slight differences between the programmes, as to the exact values of these properties and when the fluctuations occur. These variations can account for the small deviation between the two curves above. The values of the emissivity for the radiation component of heat transfer, or the convective heat transfer co-efficient used in the FIRES-T2 are not known, but it is assumed that they would not vary too much from the accepted values discussed in Section 2.1.

FIRES-T2 uses a 130 mm slab and this simulation performed in SAFIR also has a 130 mm slab resting on the top flange of the steel section. The concrete is calcareous concrete with properties as stated in EC2 as simulated in SAFIR. The properties of the concrete in the FIRES-T2 programme are not known, but it is assumed the thermal differences between types of concrete would not affect the average temperature too significantly.

Since both programmes use the same principles of heat transfer to analyse a cross section of a steel beam, these results are as expected.

4.4.2 Comparison with Firecalc:

This programme is a simple heat transfer package with capabilities to analyse protected and unprotected steel. The background information on the Firecalc programme is given in Section 2.3.2.

When plotting the standard fire as already in the Firecalc package against the ISO 834 fire used in this report, it was found that the fire time-temperature curve was not the same. On examining the raw data that is input into the Firecalc programme, it was found that the temperatures were that of the increase above ambient temperature with time as for the ISO 834 fire, but that the ambient temperature had not been added on to this increase as the formula requires. This means that the standard fire in Firecalc is always 20 °C lower than the temperatures calculated in the spreadsheet method. This data can be updated and this was done to be able to more accurately compare the data output.

The results of a comparison with the spreadsheet method, SAFIR and Firecalc for an unprotected beam of size 530UB82.0 are shown in Figure 4.14.

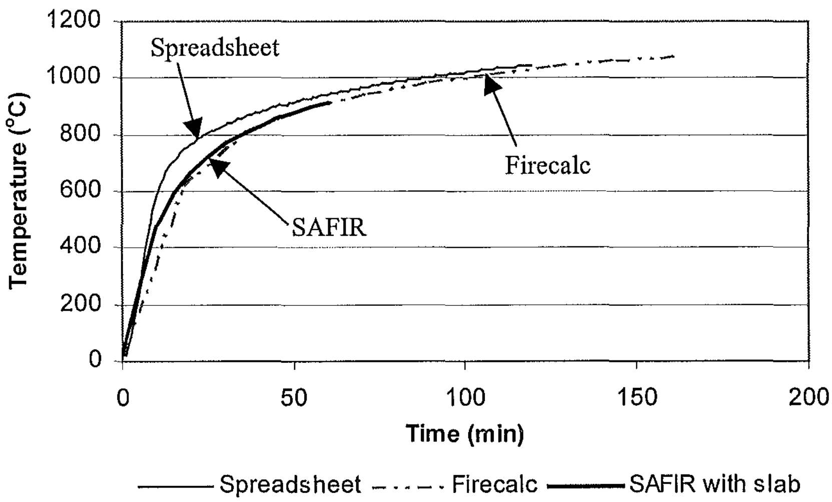


Figure 4.14: Comparison between the results from the spreadsheet method, SAFIR and Firecalc for an unprotected 180UB16.1 beam exposed on three sides to ISO 834 fire.

When comparing Firecalc and the Spreadsheet results, it appears that the Firecalc programme gives temperatures that are a lot lower which means these are rather non conservative results. When these results are compared with SAFIR, however, the time-temperature curves are very close. The Firecalc manual instructs that the programme is designed for three sided exposure, although when using the programme this information is not provided. The SAFIR simulation is one with three sided exposure with a concrete slab modelled on top of the beam as in Section 4.3.1.

The SAFIR results are much closer to the Firecalc results than the Spreadsheet results are because the Firecalc programme models a concrete slab on top of the beam as does SAFIR. The properties of the concrete are listed in the Firecalc programme with density = 2400 kg/m^3, thermal conductivity = 1.83 W/mK, and specific heat = 960 J/kgK. The thickness or width of the concrete slab are not provided in the instruction manual or the computer 'help' file. This package has many uncertainties, and assumptions have to be made concerning the affect of the slab to use the information found from the analysis.

This application has been removed from the updated version of the Firecalc menu, Firewind, so it assumed that the programming assumptions and methods have been deemed inaccurate and will therefore seldom be in use in the future. This comparison has been included in this report for completeness.

4.5 CONCLUSIONS:

The results in this section show that the empirical equations from the ECCS recommendations give better results than those equations presently found in NZS 3404, when comparisons are made with the temperatures curves from the spreadsheet method and SAFIR. This is definitely the case for four sided exposure of unprotected steel members. For three sided exposure, even though the NZS 3404 equations give a time temperature relationship that is closer to the average temperature with a concrete slab, the ECCS equations give results closer to the maximum temperature over the cross section, which is more likely to cause failure.

Therefore, the ECCS equations provide a better indication of the time and temperature that failure will occur.

The ECCS formula should have an extended temperature range to up to around 750 °C; with linear interpolation for temperatures less than 400 °C. The temperature limitations of the ECCS equations should be examined closer and adjusted so the equations can be put more to use than the limiting temperature range that is presently imposed on them. The suggestion of a maximum temperature at least 750 °C rather than the present value of 600 °C is based on the results of the comparisons made in this report only. The ECCS equations would give better and more useable results than the present formula in NZS 3404 for four sided exposure with an extended temperature range.

A concrete slab is present for most three sided cases, so the NZS formula gives a more accurate estimation of the average temperature of the steel beam for these cases but not the maximum temperature. If the ECCS equation was adopted for four sided exposure based on the evidence seen here, however, it would simplify the code to use the ECCS equation for three sided exposure also as the difference in temperature is only small, and differs conservatively from the present equations.

The spreadsheet method gives an accurate indication of the thermal response of steel members when subjected to the ISO 834 fire when compared to the steel temperatures assumed by the SAFIR programme. If the average temperature of unprotected steel is required for a calculation in a temperature or time range where the formulas are not valid, the spreadsheet method is the simplest method to use.

The time step method gives accurate results, especially for four sided exposure where there is less variation across the cross section of the member. For three sided exposure, the time step spreadsheet method gives conservative results if the beam has a slab protecting the top flange, and only the average temperature of the steel can be calculated. To analyse the maximum temperatures likely to be reached in the section a finite element programme such as SAFIR needs to be used. Although the spreadsheet offers only the average temperature of the steel, with three sided exposure with a slab present the spreadsheet gives higher temperatures which are close to the maximum because the concrete thermal affects are not accounted for.

5 CALCULATION OF STEEL TEMPERATURES FOR PROTECTED STEEL – ISO FIRE:

5.1 INTRODUCTION:

Although steel is non-combustible, it is still affected by fires because its strength becomes severely impaired by the increase in temperature. At elevated temperatures steel loses a significant amount of strength, so precautions are often required to prevent the steel from heating up too much. The methods prescribed in the New Zealand code require that results from standard fire tests be used, ie. data showing how the member will behave when subjected to elevated temperatures with the protection in place. The tests are required to give an equal or worse result than the members being designed, which means that the geometry of the beam, thickness of the protection or loading patterns must be worse or equal to the beam being considered.

The most common methods of protection include spray-on vermiculite or perlite plaster, sprayed mineral fibre or gypsum plasterboard. Varying the thickness of the insulation changes the protection offered to the steel beam, and as in Section 4, the H_p/A value of the steel member has a major influence of the energy transfer to and temperature rise in the steel. The properties of the protection also have a large impact on the results found from simulations. Slightly different methods are recommended for heavy and light protection, which is also discussed in Section 2.1.3.

The simplified method for light protection, which neglects the heat capacity of the insulation, is compared with retaining the heat capacity term in the formula. Comparisons are also made here between the spreadsheet method, SAFIR and the equations recommended by ECCS for protected members.

5.1.1 Assumptions:

The properties of steel used in the spreadsheet method are kept constant, namely the density, ρ = 7850 kg/m^3 and specific heat, c_s = 600. SAFIR uses varying values according to information stored in the programme from EC3, as with unprotected steel. The thermal properties of the insulation is also assumed to remain constant for the spreadsheet method, while again SAFIR has variations for these properties with temperature.

The beam is assumed to have an even coverage of the spray on protection applied over the cross section, and the thermal properties of the insulation is assumed to be uniform. The ability of the protection to remain on the steel member is termed the 'stickability'. It is assumed here that this is adequate and that the protection remains on the member throughout the test. Where the protection is in board form, the board is assumed to have uniform properties, to be of constant thickness and adequately attached to the steel member.

The average temperature of the SAFIR results has been compared with the spreadsheet method results. For the purposes of this report, the average is assumed to be the average temperature of all the elements in the cross section of the beam. No consideration has been made to the size of the particular element or the location on the cross section. For comparisons with the spreadsheet method this is acceptable, since the spreadsheet calculates the average steel temperature. For strength analyses however, the maximum temperature is important for the failure or limiting temperature of the steel section.

The other assumptions as made in Section 4.1.1 regarding the temperature of the air around the beam and the temperature distribution throughout the beam are valid here. The temperature distribution across the cross section of the beam is not assumed to be constant for the situations where a concrete slab has been added to the beam as this addition to the profile lowers the temperature on the top flange significantly.

5.2 RESULTS FOR FOUR SIDED EXPOSURE WITH HEAVY PROTECTION:

In this section comparisons between the average temperature of protected steel exposed to the ISO fire on four sides is made. The results of SAFIR and calculations made by the spreadsheet method give time temperature curves, which are compared with the ECCS approximate formulas. There are no simple formulas in the New Zealand Steel Code for protected members, as test data is relied on to provide an estimation of the behaviour of protected steel members.

Properties of spray on protection: Fendolite by Firepro Safety Ltd

Specific heat, $c_i = 1100$ J/kg K

Thermal conductivity, $k_i = 0.19$ W/m K

Density, $\rho_i = 775$ kg/m^3

Thickness, $d_i = 0.02$ m

5.2.1 Results from a simulation with the SAFIR programme:

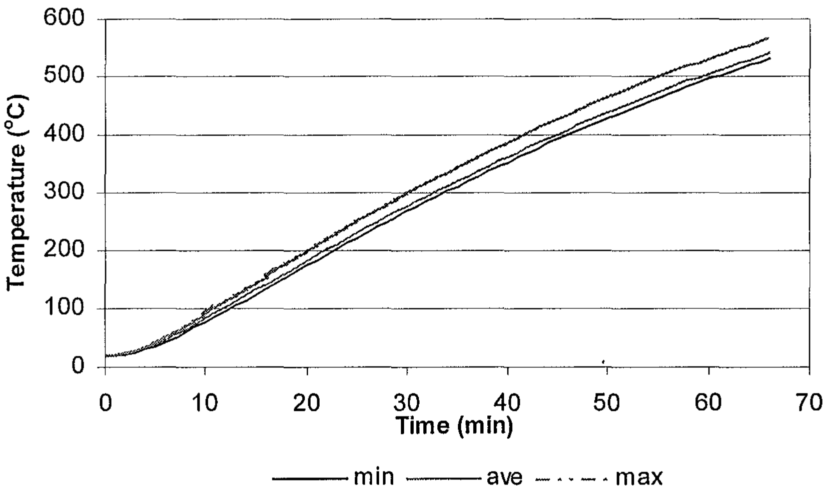


Figure 5.1: Time temperature curve from a SAFIR simulation showing the variation of temperature of different elements in the beam for four sided exposure to an ISO fire for a 530UB82 beam.

Figure 5.1 shows the variation of temperature across the cross section of the steel beam. From examining the three SAFIR curves, it is found that the difference between the maximum and minimum temperatures is greater than that found with four sided unprotected steel, but less variation than three sided unprotected steel. The maximum temperatures are found at the centre of the web, as the web is the longest and thinnest section of the beam cross section. The coolest part of the beam is the location of the centre of the flange, where the web and the flange intersect. This is due to there being a larger mass in this part of the cross section than elsewhere, and more insulation protects the internal corner of the beam as shown in Figure 5.2:

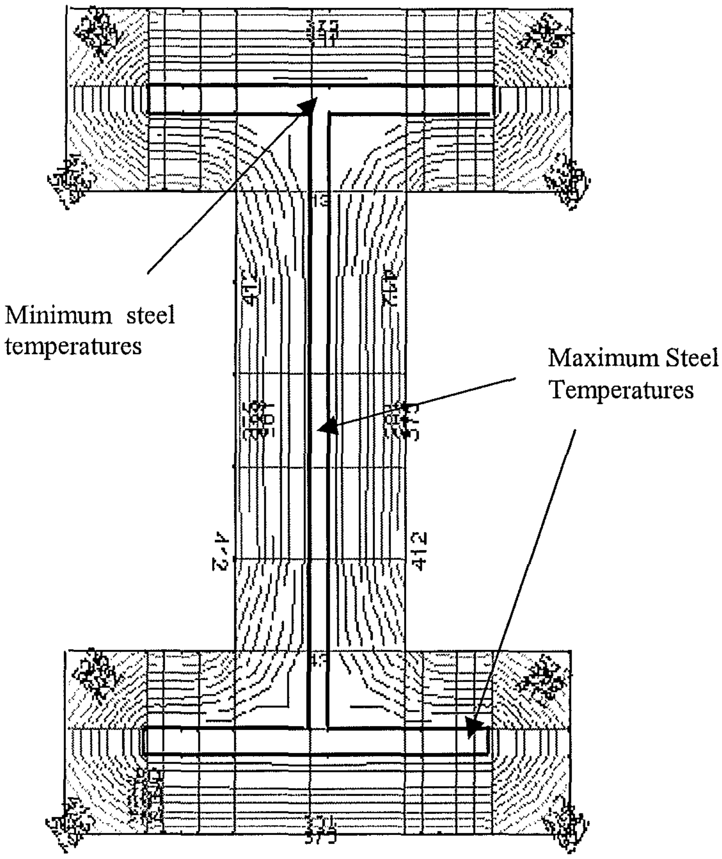


Figure 5.2: Location of the maximum and minimum temperatures on the cross section of a steel beam with spray on protection

These minimum temperatures are in different locations to where the lowest temperatures are found in unprotected steel, (See Section 4.2.1), as the lowest temperatures in these cases are found midway between the flange tip and intersection with the web, or at a quarter of the flange length from the flange tip. The temperature at the intersection of the web and the flange in unprotected steel is only slightly higher than the temperature of the quarter flange points, but with protected steel there is a larger temperature gradient along the flange.

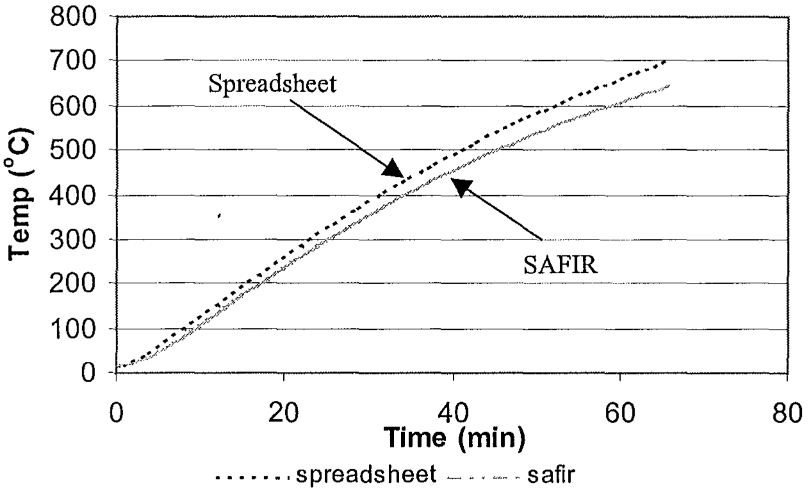
The difference between the maximum and minimum temperatures with protected steel increases as the test progresses, as in Figure 5.1, which is the opposite of the behaviour seen with unprotected steel. At the start of the test all parts of the beam are immediately protected from the fire, so the initial heating of the steel is slow in all areas of the beam. As the test continues the areas of the beam that are most susceptible to heating, heat up more than those parts of the beam which are more protected due to the geometry of the beam, ie. the thickness or length of the segment, or the location of the point, ie. the centre of the web compared with the corner of the flange-web intersection.

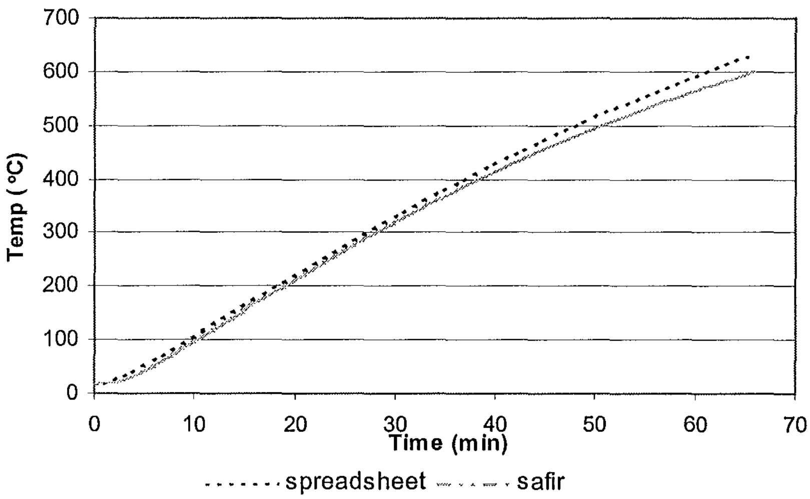
5.2.2 Heavily Protected Beam with Four Sided Exposure:

Four sided exposure is modelled in the SAFIR programme using insulation with the properties stated earlier in Section 5.2. The steel section is protected on all four sides, and an ISO 834 fire is subjected all sides of the protection. The temperature variation across the cross section of the element is small, and of similar proportions to that of four sided exposure for unprotected steel.

The results from SAFIR and from the spreadsheet method are compared, and these are also graphed against the estimations from the ECCS equations in Section 5.2.3. There are no formulas provided in NZS 3404 for protected steel members.
Figure 5.3 a-c show the results from four sided exposure to the standard ISO 834 fire, for 66 minutes. The graphs show a very close correlation between the temperatures predicted by the spreadsheet and the average temperatures found from the SAFIR simulation. The spreadsheet method gives higher temperatures than SAFIR at lower temperatures of the test, but the difference between the average SAFIR temperature and the spreadsheet temperature increases as the beam gets hotter, with the spreadsheet temperatures exceeding those determined from SAFIR.

This is again due to the thermal properties of steel remaining constant with the spreadsheet method, but varying with SAFIR. The curves tend to separate more as the temperature increases, and the spread increases greatly at around 650 °C to 700 °C as this is where the thermal properties of SAFIR deviate most from the constant value of 600 J/kg K that is used in the spreadsheet.





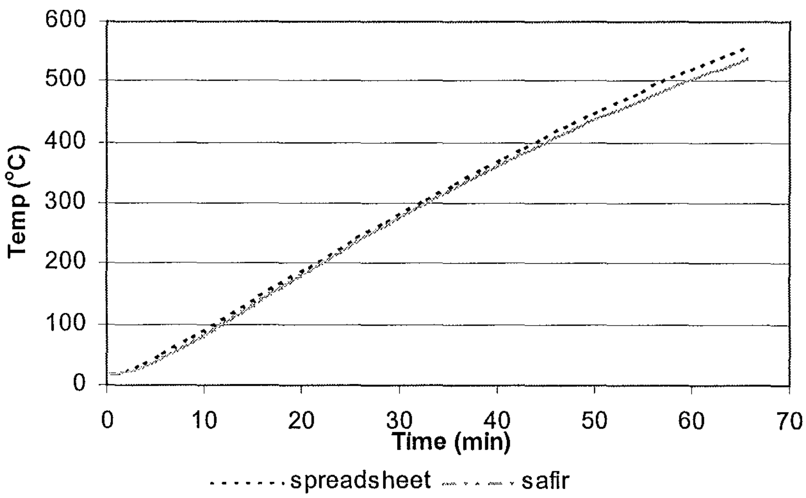


Figure 5.3 a-c: Comparison between the results from SAFIR and the spreadsheet method for Fendolite protected steel beams with four sided exposure to the ISO standard fire. From top to bottom beam sizes a. 180 UB 16.1, b. 310 UB 40.4 and c. 530 UB 82.0

Figure 5.3 a-c show the results from four sided exposure to the standard ISO 834 fire, for 66 minutes. The graphs show a very close correlation between the temperatures predicted by the spreadsheet and the average temperatures found from the SAFIR simulation. The spreadsheet gives slightly higher temperatures than SAFIR at lower temperatures of the test, but the difference between the average SAFIR temperature and the spreadsheet temperature increases as the beam gets hotter, with the spreadsheet temperatures exceeding those determined from SAFIR.

This is again due to the thermal properties of steel remaining constant with the spreadsheet method, but varying with SAFIR. The curves tend to separate more as the temperature increases, and the spread increases greatly at around 650 °C to 700 °C as this is where the thermal properties of SAFIR deviate most from the constant value of 600 J/kg K that is used in the spreadsheet.

The deviation from the spreadsheet is more pronounced with protected steel than from the unprotected members considered in Section 4 due to the rate of heating that the beam experiences. Since the rate of heating is much slower due to the protection applied to the beam, the time period that the temperature of the steel remains at around 650 °C to 700 °C is longer than when no protection is added. Therefore overall the difference in temperature between the results from the SAFIR programme and from the spreadsheet method from keeping the properties constant in the spreadsheet is more marked for protected steel than for unprotected steel.

The properties of this insulation are such that the equation used in the spreadsheet formula accounts for the heat absorbed by the insulation. If a lighter insulation was used, the equation could be simplified by assuming the heat absorbed by the insulation is negligible as described later in Section 5.3.

The heavier beams appear to have better agreement between the results from SAFIR and the spreadsheet method than the light 180 UB 16.1 beam. This is because in the time scale used in SAFIR for the comparisons, the heavier and thicker beams have not yet reached 650 °C where the curves generally tend to deviate more from each other. Even with this reasoning however, the lighter beam does have a larger spread between the spreadsheet and SAFIR results at 500 °C than the other two heavier beams studied in this report. The temperature reaches 500 °C after 45 minutes from the SAFIR simulation for the lightest beam, while the spreadsheet gives a time of 41 minutes. This is longer than the difference in times for the two other beams analysed here which both had a time difference of 2.5 minutes between the two simulations.

5.2.3 Comparison with the ECCS equation:

The formula recommended by ECCS for protected steel is:

$$t = 40(T_l - 140)\left[\left(\frac{d_i}{k_i}\right)\left(\frac{A}{H_p}\right)\right]^{0.77} \qquad 5.1$$

where T_l = the limiting temperature of the steel (°C)

k_i = the thermal conductivity of the insulation (W/m K)

d_i = the thickness of the insulation (m)

This equation is valid for the temperature range of 400 °C to 600 °C, for section factors between 10 and 300 m^{-1}, for times between 30 and 240 minutes and for ratios of insulation thickness to thermal conductivity from 0.10 to 0.30 m^2 °C/W.

The section factors forfoursided exposure for the beams are 178 m^{-1} for 530 UB 82, 241m^{-1} for 310 UB 40.4 and 334 m^{-1} for 180 UB 16.1 beams, so the lightest beam is out of the size range recommended. The insulation thickness to conductivity ratio is $\frac{0.02}{0.19} = 0.105$ so this fits within the required range.

Equation 5.1 is intended for light protection, for which the properties of the insulation must meet the following criteria, from equation 2.4:

$$\rho_s c_s A_s > 2\rho_i c_i A_i$$

For Fendolite, where the properties are as given in Section 5.2, the equality for the 530 UB 82.0 beam becomes:

7850*600*10500 > 2*775*1100*(1869*20)

$4.93 \times 10^{10} > 6.37 \times 10^{10}$

A_i is the cross sectional area of the insulation. For the purposes of this inequality, this is taken as the thickness of the insulation multiplied by the perimeter of the steel. Since this equality in not satisfied, the protection can not be termed 'light' and the formula must be modified to allow for this.

Two methods of modifying this equation to allow for heavier insulation have been found, the ECCS recommendations, (1985), suggest substituting $\left(\frac{d_i A}{H_p}\right)$ in the power bracket with

$$\left(\frac{d_i A}{H_p}\right)_{\text{mod}} = \frac{d_i A}{H_p} + \frac{c_i \rho_i d_i^2}{2 c_s \rho_s} \qquad 5.2$$

Purkiss, (1996), recommends a slightly different variation of this, as below:

$$\left(\frac{d_i A}{H_p}\right)_{\text{mod}} = \frac{d_i A}{H_p} + \frac{\rho_i d_i^2}{\rho_s} \qquad 5.3$$

The formula has been simplified from that suggested by ECCS by assuming that for heavy insulation the specific heat of the insulation will be approximately twice that of steel, or around 1200 J/kg K. This value is close to that assumed for vermiculite protection, which is 1100 J/kg K in this report. This modification effectively increases the thermal capacity of the steel by adding half the thermal capacity of the insulation.

For the purposes of this report however, the original ECCS modified equation has been used to compare the formulas for protected steel members from the results calculated in the spreadsheet formula.

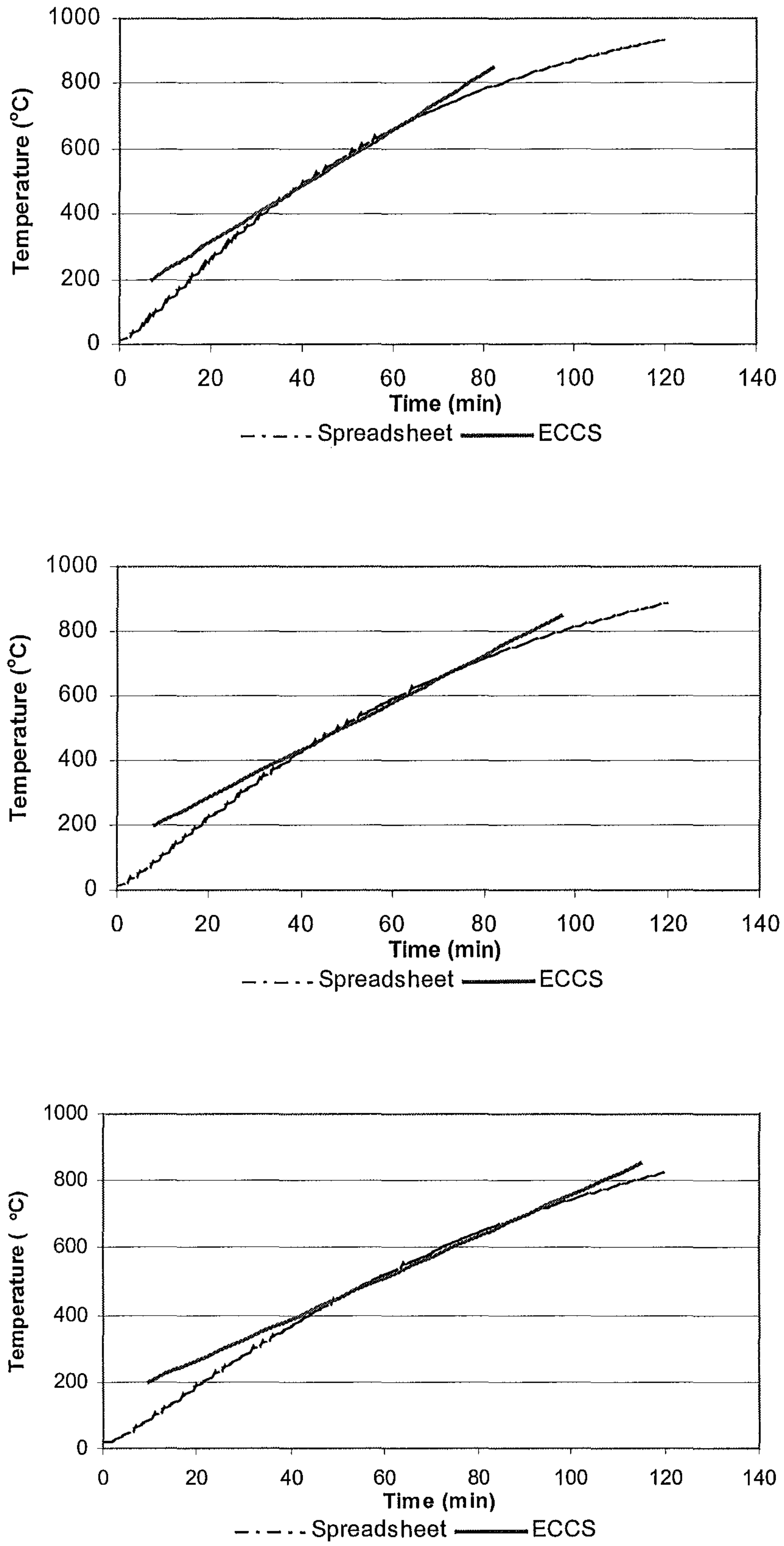


Figure 5.4 a-c: Comparison of the linear equations provided by NZS 3404 and ECCS with the temperatures obtained from the spreadsheet method with four sided exposure to an ISO 834 fire. From top to bottom a. 180 UB 16, b. 310 UB 40.4 and c.530 UB 82.0

As can be seen from Figure 5.4 a-c, the line resulting from this formula fits well with the spreadsheet curve on each graph. The temperature range that this equation is valid for is from 400 °C to 600 °C but the upper limit of this could be extended to 800 °C from the evidence seen here. The lower limit could also be extended beyond the range suggested, to around 300 °C, although linear interpolation for temperatures below 400 °C from a starting temperature of 20 °C as is recommended with the formulas from NZS 3404 would be a better option.

The ECCS formula for the light steel beam appears to have good correlation with the spreadsheet curve even though the beam size has a section factor outside of the recommended range. For unprotected steel this light beam gave results that did not fit with the SAFIR curves for four sided exposure, see Section 0, although for three sided exposure for unprotected beams the results fit well.

There appears to be little difference in the accuracy of the formula between the three beam sizes used here, and the formula appears to give a very accurate estimation of the temperature of the steel during the temperature range of 350 °C to 800 °C. Again the SAFIR curves are used to compare the accuracy of the formulas as this programme shows the thermal response of steel to great accuracy. Using the modified ECCS equation gives excellent results when compared with the results from the SAFIR programme. Purkiss' simplified version of the modified equation also gives good accuracy, but the assumption that the specific heat of the insulation is twice that of steel is a bit non conservative, as the specific heat values for heavy insulation can vary significantly.

5.3 RESULTS FOR FOUR SIDED EXPOSURE WITH LIGHT PROTECTION:

The same comparisons that are made with heavy protection are applied in this section to examine the effect of the simplifications and assumptions made with light protection. The insulation used to model the effect of light protection is Mandolite, by Firepro. The properties of this are as below:

Mandolite by Firepro Safety Ltd

Specific heat, $c_i = 1100$ J/kg K

Thermal conductivity, $k_i = 0.1$ W/m K

Density, $\rho_i = 362$ kg/m^3

Thickness, $d_i = 0.02$ m

5.3.1 Lightly Protected Beams with Four Sided Exposure:

There is a simplified version of the spreadsheet method for steel members with light insulation. This is covered in Section 2.1.3, and involves neglecting the insulate heat capacity term in the original formula.

In this section, the results from an analysis with SAFIR are compared with the results from calculations by the spreadsheet method, both the full equation and the simplified version. The time temperature curves of these are then compared with the ECCS, (1985) equations for protected steel beams with light insulation.

For simplification of distinguishing between the results from the two spreadsheet analyses, the following notation is used:

Spreadsheet 1 – The temperature rise of the member has been calculated with the full equation, accounting for the effects of the heat capacity of the insulation.

Spreadsheet 2 – The temperature rise of the member has been calculated with the simplified equation, neglecting the effects of the heat capacity of the insulation.

The insulation is termed light due to its compliance with equation 2.4:

$$\rho_s c_s A_s > 2\rho_i c_i A_i$$

Substituting the appropriate values for each case, and using A_i as the perimeter of the steel multiplied by the thickness of the insulation (20 mm)

530 UB 82.0 beam

$H_p/A = 178$ m^{-1}, $A_s = 10500$ mm^2, $H_p = 1869$ mm

7850*600*10500 >2*300*1100*(1869*20)

$4.95 \times 10^{10} > 2.47 \times 10^{10}$

310 UB 40.4 beam

$H_p/A = 241\ m^{-1}$, $A_s = 5210\ mm^2$, $H_p = 1256$ mm

7850*600*5210 >2*300*1100*(1256*20)

$2.45 \times 10^{10} > 1.66 \times 10^{10}$

180 UB 16.1 beam

$H_p/A = 334\ m^{-1}$, $A_s = 2040\ mm^2$, $H_p = 681$ mm

7850*600*2040 >2*300*1100*(681*20)

$9.61 \times 10^{9} > 8.99 \times 10^{9}$

Clearly the heat capacity of the insulation described above is significantly less than the steel heat capacity, and therefore can be neglected, when it is considered that for the insulative term to be neglected it must be less than half that of the steel.

The results of the simulations in SAFIR and from the two spreadsheet calculations are shown in Figure 5.5 a-c.

Figure 5.5 a-c shows that with light insulation there is a small difference between the two spreadsheet formulas used. The temperatures from Spreadsheet 1, with the heat capacity of the insulation included are slightly higher than the temperatures from Spreadsheet 2 with the heat capacity neglected. This is as expected because even if the effect of the insulation of the temperature rise of the steel is small, there is still some effect from the heat capacity of the insulation.

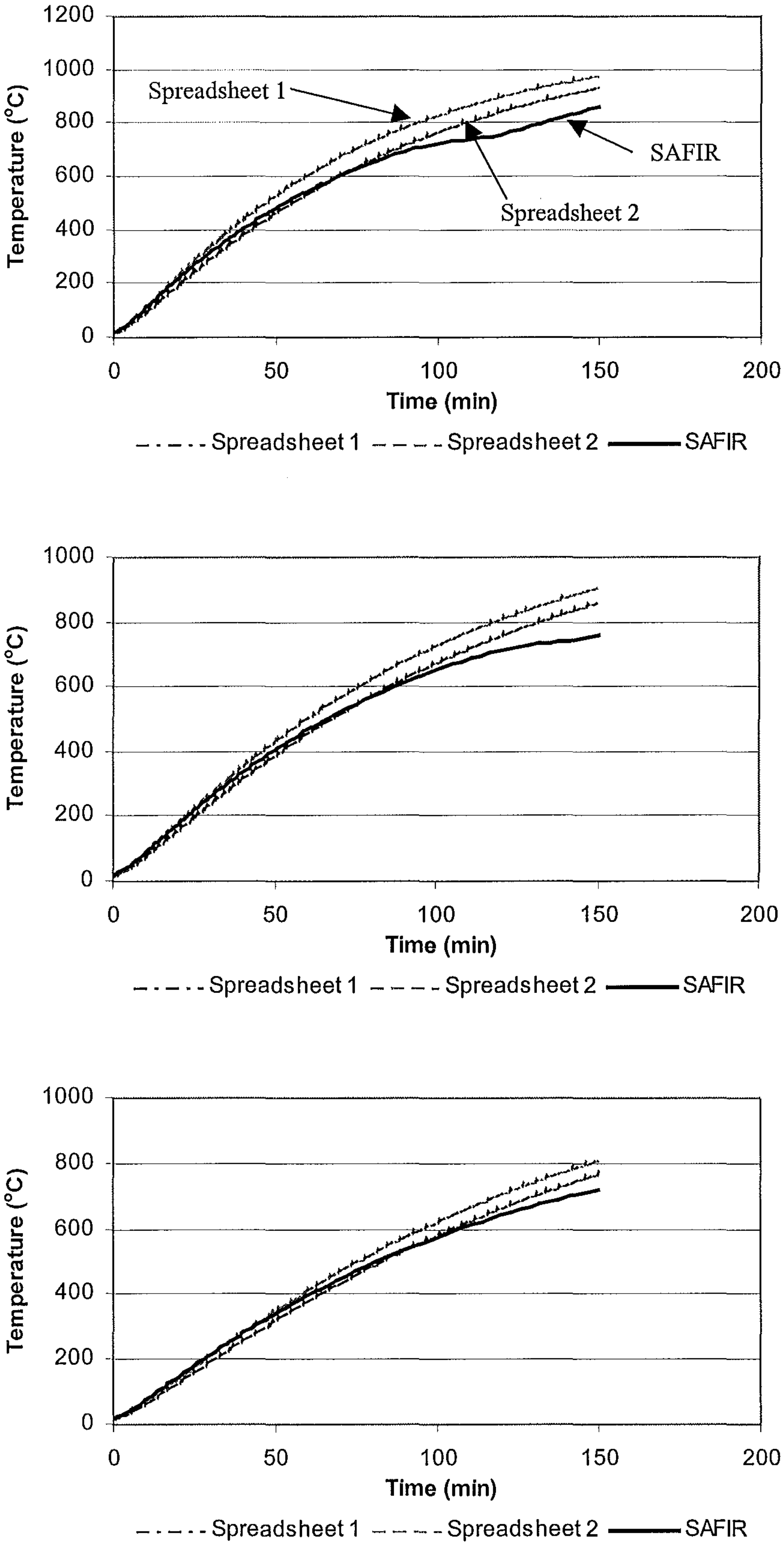


Figure 5.5 a-c: Comparison between the results from SAFIR with the simplified and full spreadsheet methods for a beam with light insulate protection. From top to bottom: a. 180 UB 16, b. 310 UB 40.4 and c.530 UB 82.0

The SAFIR results fit between the two spreadsheet results for most of the test and as in all simulations made in this report, the rate of temperature rise decreases at about 650 °C when the higher specific heat becomes a larger factor in the temperature rise of the steel. The results from the Spreadsheet 2 analysis are very similar to the results from the Spreadsheet 1 analysis, with a maximum difference of around 50 °C. Since simplifying the formula used in the spreadsheet for light protection gives higher temperatures, the simplified formula can be used with confidence instead of the full equation provided the criteria from equation 2.4 is met. The insulation will always affect the temperature of the steel to some amount so the full spreadsheet analysis is acceptable to use in place of the simplified version if preferred.

Assuming the SAFIR programme gives an accurate portrayal of the behaviour of the steel beam when protected by the insulation described, the full equation gives slightly lower temperatures and therefore non-conservative results at the beginning of the test. The maximum temperature deficit of temperatures found from the spreadsheet with the heat capacity included, compared with the average SAFIR results is 20.3 °C, which occurs when the temperature is about 250 °C. Although a difference of around 10 % is reasonably substantial, it is not of too much importance here due to that the steel member would not have lost a significant amount of strength at this temperature.

The spreadsheet temperatures are greater than the steel temperatures after 93 minutes of the test, when the temperature is about 550 °C, which is much closer to the limiting temperature of steel. After 93 minutes the SAFIR curve drops below the spreadsheet curves at a faster rate due to the thermal properties of the steel in the SAFIR programme.

The curve from the simplified spreadsheet method is consistently higher than both the full spreadsheet curve and the SAFIR curve. At the very start of the test the SAFIR curve is slightly higher than the simplified spreadsheet curve, but this could be due to the slow starting conditions found with the spreadsheet method. The maximum difference is 3 °C and after 30 minutes the spreadsheet method curve is above the SAFIR curve. The maximum temperature where the SAFIR temperature is highest is when the temperature of the steel is around 220 °C, which is much lower than the limiting temperature of steel, and therefore occurs at a 'safe' temperature.

Figure 5.5 shows that the simplified formula is adequate to estimate the temperatures of protected steel beams, and that although it gives higher temperatures, this makes the results conservative. The difference between the simplified spreadsheet curve and the SAFIR curve tends towards 150 to 200 °C when the temperature is around 700 °C in Figure 5.5 a-c due to the difference in thermal properties used in the calculation of the results.

When the thermal properties are accounted for with the spreadsheet this difference decreases and tends more towards zero as shown in Figure 5.6. The spreadsheet analyses have been performed with varying specific heat values with changes made from equation 1.4 in Section 1.6.2.

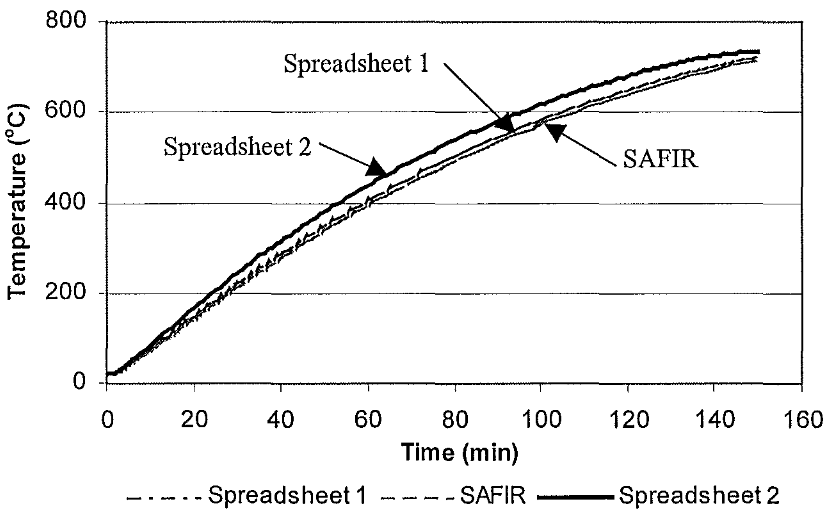


Figure 5.6: Comparison between the spreadsheet methods and SAFIR with varying thermal properties in the spreadsheet programme with the 530 UB 82.0 beam.

The spreadsheet 2 curve with the heat capacity of the steel included in the calculations and with varying specific heat is very close to the SAFIR curve, with a maximum temperature difference of about 10 °C which occurs at higher temperatures. This is around half of the difference that was observed with a constant specific heat being used in the spreadsheet method, but since the difference is small in both cases; the simple method of keeping the specific heat constant appears to be more reasonable.

Using a specific heat that varies with temperature in the spreadsheet method shows how closely the spreadsheet method results match those that are given by the finite element computer programmes. Because the spreadsheet method is much easier to access and work compared with the computer programmes, for thermal calculations of simply supported beams with four sided fire exposure. this method is the best to use.

5.3.2 Comparison with the ECCS Formula:

Comparisons with the formulas recommended by ECCS have been plotted against the results from the SAFIR simulations and the simplified spreadsheet results in Figure 5.7 a-c. Equation 5.1, by ECCS used in Section 5.2.3, is used in its original form without the modification for heavy insulation, since the properties of Mandolite satisfy the conditions of equation 2.4, as shown in Section 0.

Figure 5.7 a-c shows the accuracy of the ECCS formula when applied to steel sections with light protection. The ECCS formula is compared to results from the spreadsheet method with the light insulation simplification, but with a constant value for the specific heat of steel. Results from SAFIR are also included to compare the formula with 'real' behaviour of steel under the conditions of the analysis.

When light protection is used as in Figure 5.5 a-c, the unmodified spreadsheet method has slightly lower temperatures than the simplified version. The SAFIR results are lower than the results from both spreadsheet methods due to the changing thermal properties installed in the programme. The ECCS equation has the best correlation with the spreadsheet 2 curve, which neglects the heat capacity of the insulation term. The section factor for the lightest beam, 180UB16.1, is out of the recommended range of beam sizes for the ECCS equation, but the formula predicts the temperatures equally well for this beam as with the other beam sizes.

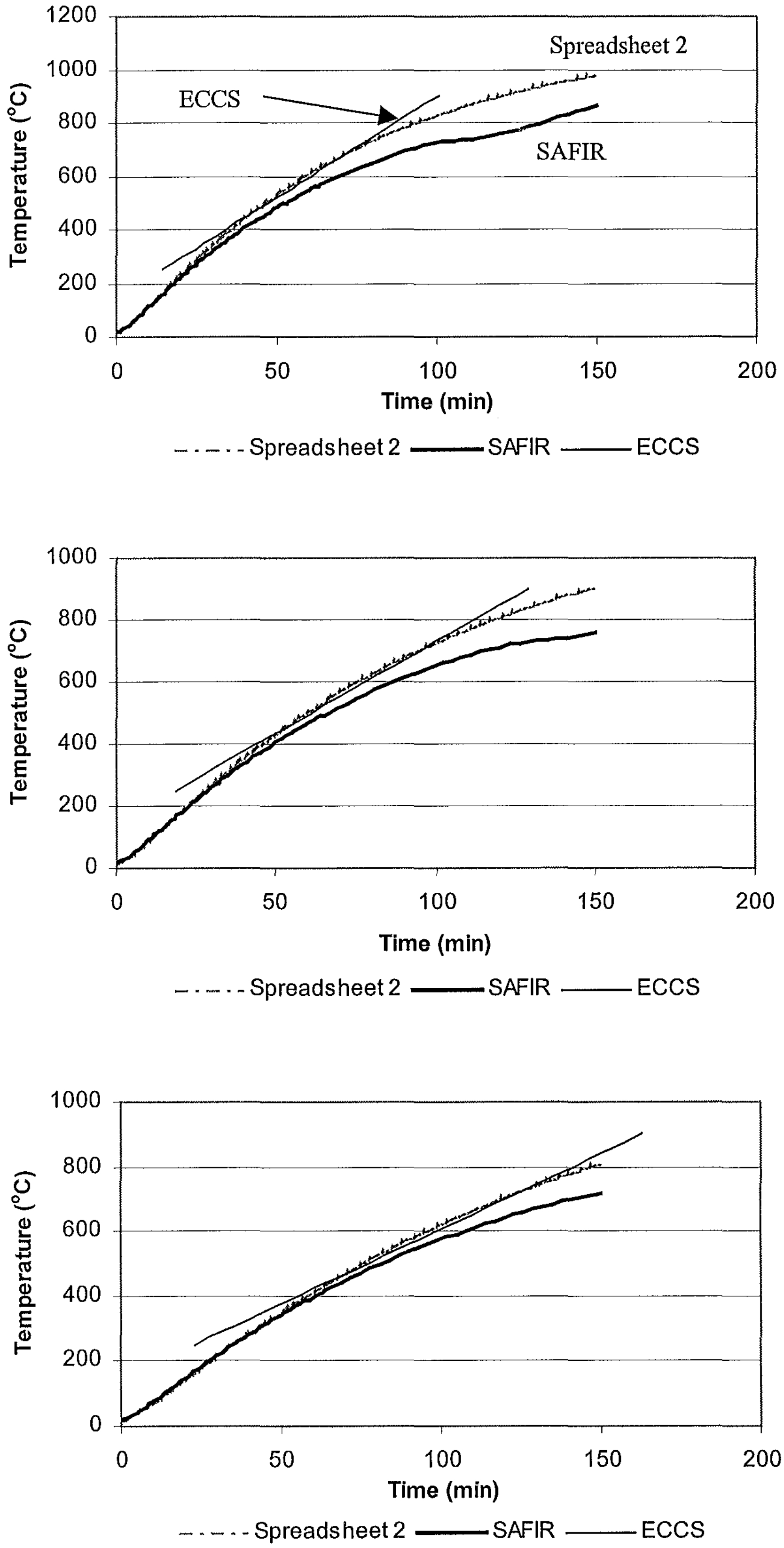


Figure 5.7 a-c: Comparison between the results from the two spreadsheet methods, SAFIR and the ECCS recommended formula for steel with light insulation protection. From top to bottom: a. 180 UB 16, b. 310 UB 40.4 and c.530 UB 82.0

From Figure 5.7 a-c, it appears that the ECCS equations give a good indication of the average temperatures of the steel members when subjected to an ISO 834 fire. The temperature range that these formulas are valid for is from 400 °C to 600 °C. This upper limit could be extended to 800 °C based on the results of Figure 5.7 a-c, and the section size limitations for protected steel members could also be extended, although the current range is quite substantial and would cover most beams sizes currently. The time period for which the formula is valid does not appear to be a significant factor, because although the results here are sometimes out of the time range suggested, the lines tend to fit to the SAFIR or spreadsheet curves regardless of the time when these temperatures occur.

These results for light protection support the comments made in Section 5.2.3 about the ECCS equations for steel members with heavy insulation. The same changes to the temperature limitations of the equations are made for both the heavy and light protection forms of the equation and the other time and size limitations appear unnecessary for both forms.

5.4 RESULTS FOR FOUR SIDED EXPOSURE WITH BOX PROTECTION:

Four sided box protection is considered in this section. For box protection, the section factor is calculated by a different procedure to that of protected beams with spray on protection. The heated perimeter, H_p, for four sided exposure is the perimeter of the box, or twice the height and depth of the section, while the area, A, is the cross sectional area of the steel section. This gives a smaller section factor than with spray on protection and therefore a thicker effective width.

In this section the box protection is considered to be of GIB© Board. The properties of the insulate board are used as follows, Thomas, (1997):

Specific heat, $c_i = 1700$ J/kg K

Thermal conductivity, $k_i = 0.25$ W/m K

Density, $\rho_i = 600$ kg/m^3

Thickness, $d_i = 0.02$ m

5.4.1 Steel Beams with Box Protection:

With box protection, the insulation is not in contact with the steel section at all points on the perimeter. This means that radiation and convection from the inner or unexposed side of the insulation board are components of the heat transfer to the steel beam, as well as conduction from the areas of the board in direct contact with the beam.

The board insulation qualifies as heavy insulation due to equation 2.4

$$\rho_s c_s A_s > 2\rho_i c_i A_i$$

The values for this case give the following calculation for a 530 UB82.0 beam: The height and width of the beam are 528 and 209 mm respectively.

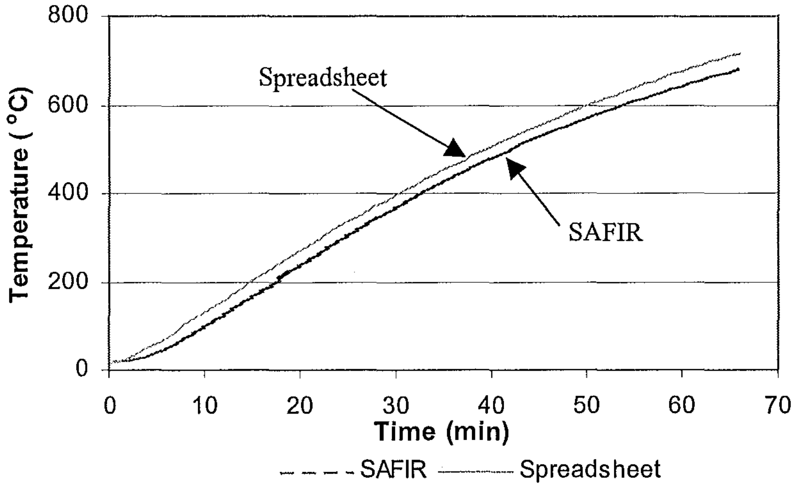
7850*600*10500 > 2*600*1700*(20*(2*{528+209}))

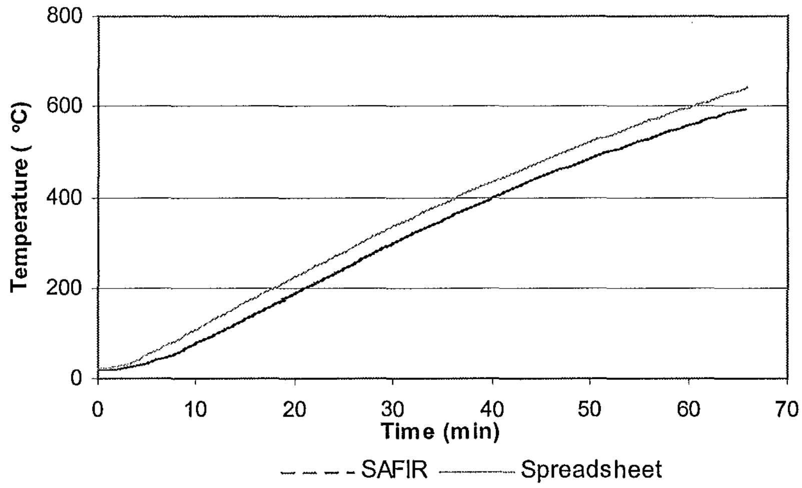
$4.95 \times 10^{10} > 6.01 \times 10^{10}$

Since the equation is not satisfied it follows that the insulation is heavy and the simplification of the spreadsheet formula may not be made. The results from simulations in SAFIR and from the spreadsheet method are shown in Figure 5.8 a-c.

The results from the spreadsheet method are consistently higher than the results given from the SAFIR programme, however they follow the same general rate of increase. The larger difference between the two curves than that observed with the spray on heavy protection is due to the assumptions made in the spreadsheet regarding one dimensional heat transfer by conduction. With box protection there are other transfer modes present and allowed for by SAFIR but not accounted for with the spreadsheet method.

SAFIR takes account of the cold surface convective coefficient, which is assumed to be 9 W/m^{2}K. This is the convection coefficient from the cool surface of the insulation. Radiation from the cold surface of the insulation is also accounted for by SAFIR, but not the spreadsheet method. A relative emissivity of 0.5 is used in the SAFIR programmes and it is assumed that this value is used for the radiation from the internal surface of the insulation to the steel.





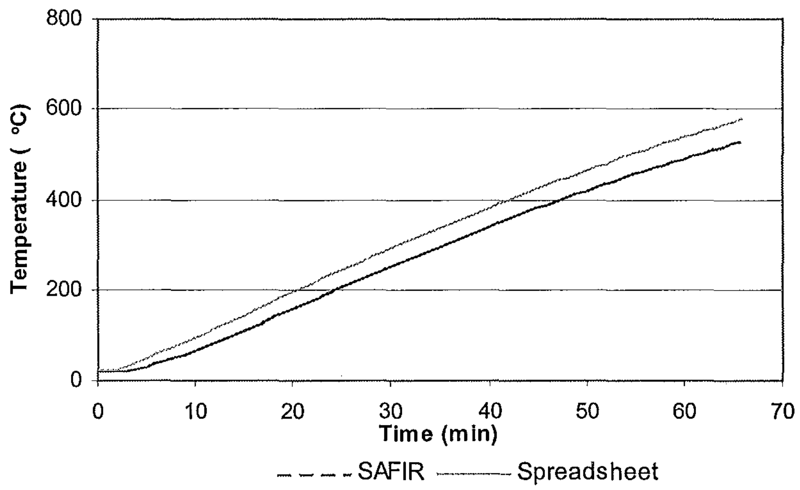


Figure 5.8 a-c: Comparison between the results from the spreadsheet method and SAFIR for protected steel beams with 20 mm board protection From top to bottom: a. 180 UB 16, b. 310 UB 40.4 and c.530 UB 82.0

The spreadsheet method gives temperatures greater than that of SAFIR even though SAFIR accounts for more heat transfer modes, because the spreadsheet method assumes that the insulation protection is in contact with the steel section for the whole perimeter, and transfers energy by conduction to the beam over the full perimeter.

The H_p/A value is smaller with box protection so the spreadsheet distinguishes that as a thicker beam. For a BHP-530 UB 82.0 steel beam, the H_p/A value for spray on protection is 178 m^{-1}, which gives a effective width steel thickness of the inverse of this which is 5.6 mm. With box protection added to the same beam, the H_p/A value changes to 140, giving an effective steel thickness of 7.1 mm. The thicker section should give lower temperatures for the beam, and when the H_p/A value is decreased to those more equal to that of three-sided exposure, the results become closer to those found from SAFIR. With the spreadsheet 'seeing' the beam as a thicker section, it is assumed the temperatures would be lower than the results from SAFIR as thicker members take longer to heat up than thin members do. Since this does not occur this suggests that the energy received by the beam through conduction through the insulation as calculated in the spreadsheet, is much more than the radiation and convection components as modelled in the SAFIR programme.

5.5 RESULTS FOR FOUR SIDED EXPOSURE WITH THICK PROTECTION:

In this section, the thickness of the insulation has been increased to 40 mm, rather than 20 mm as used in Sections 5.2-5.4. The one dimensional model which the spreadsheet equations are based on requires that the ratio of the outside perimeter to the inside perimeter is not too large, so that the one dimensional assumptions are valid. If the ratio becomes too large, the calculations will give temperatures that are too low, and a two dimensional heat flow analysis would be required.

To examine the limits of the thickness of the insulation, this section uses thicker insulation. The insulation type is Fendolite, as used in Section 5.2. This insulation is considered heavy and has thermal properties as below:

Properties of spray on protection: Fendolite by Firepro Safety Ltd

Specific heat, $c_i = 1100$ J/kg K

Thermal conductivity, $k_i = 0.19$ W/m K

Density, $\rho_i = 775$ kg/m^3

Thickness, $d_i = 0.02$ m

5.5.1 Results from a Simulation in the SAFIR programme:

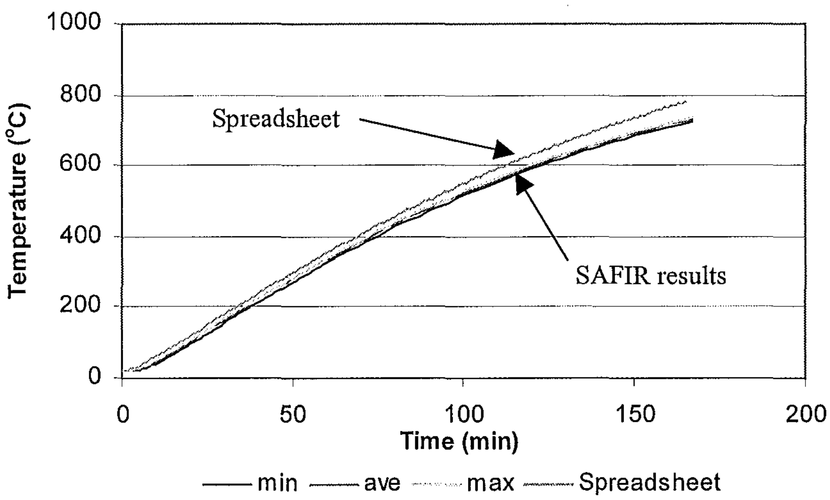


Figure 5.9: Maximum, average and minimum temperatures found from a SAFIR simulation of a 530 UB 82.0 beam exposed to the ISO 834 fire on 4 sides, with 40 mm heavy protection

Figure 5.9 above shows the variation of temperature across the cross section of the steel section with time. The temperature of the steel is almost constant across the cross section of the beam during the fire test. Comparing the difference between the maximum and minimum temperatures found in SAFIR with thick protection from Figure 5.9 with those with thinner protection from Figure 5.1 highlights how the thicker protection slows down the heating of the steel. The temperature of the steel reaches 500 °C in around 60 minutes when 20 mm of protection is applied to the 530UB82.0 beam, but it requires around 100 minutes to reach this temperature when 40 mm of protection is added.

The time-temperature curve of the spreadsheet results is also plotted in Figure 5.9. The spreadsheet still gives slightly higher temperatures than SAFIR throughout the time calculated here, which is not the results expected. Gamble, (1989) predicted that members with thicker insulation would give non conservative temperatures, ie. temperatures that are too low. Comparing the difference between the SAFIR and spreadsheet results from Figure 5.9 with the difference between the two methods in Figure 5.3 in Section 5.2.2, however, suggests that the temperatures calculated with thicker protection applied to the steel do give results that are closer to the SAFIR results and therefore slightly less conservative than with thin protection.

5.5.2 Comparison with the ECCS equation:

Figure 5.10 compares the results from the spreadsheet method and the average temperature from the results from SAFIR, with the ECCS equations for members with heavy protection. These equations are stated in Section 5.2.3. The suggested range for the ratio of insulation thickness to conductivity is $0.1 < d_i/k_i < 0.3$. For thick insulation protection of Fendolite, this ratio becomes 0.21, which is in the centre of the range, while with the thinner, 20 mm, protection in Section 5.2.3 this ratio gave a value of 0.105 which is much closer to the lower limit of the formula.

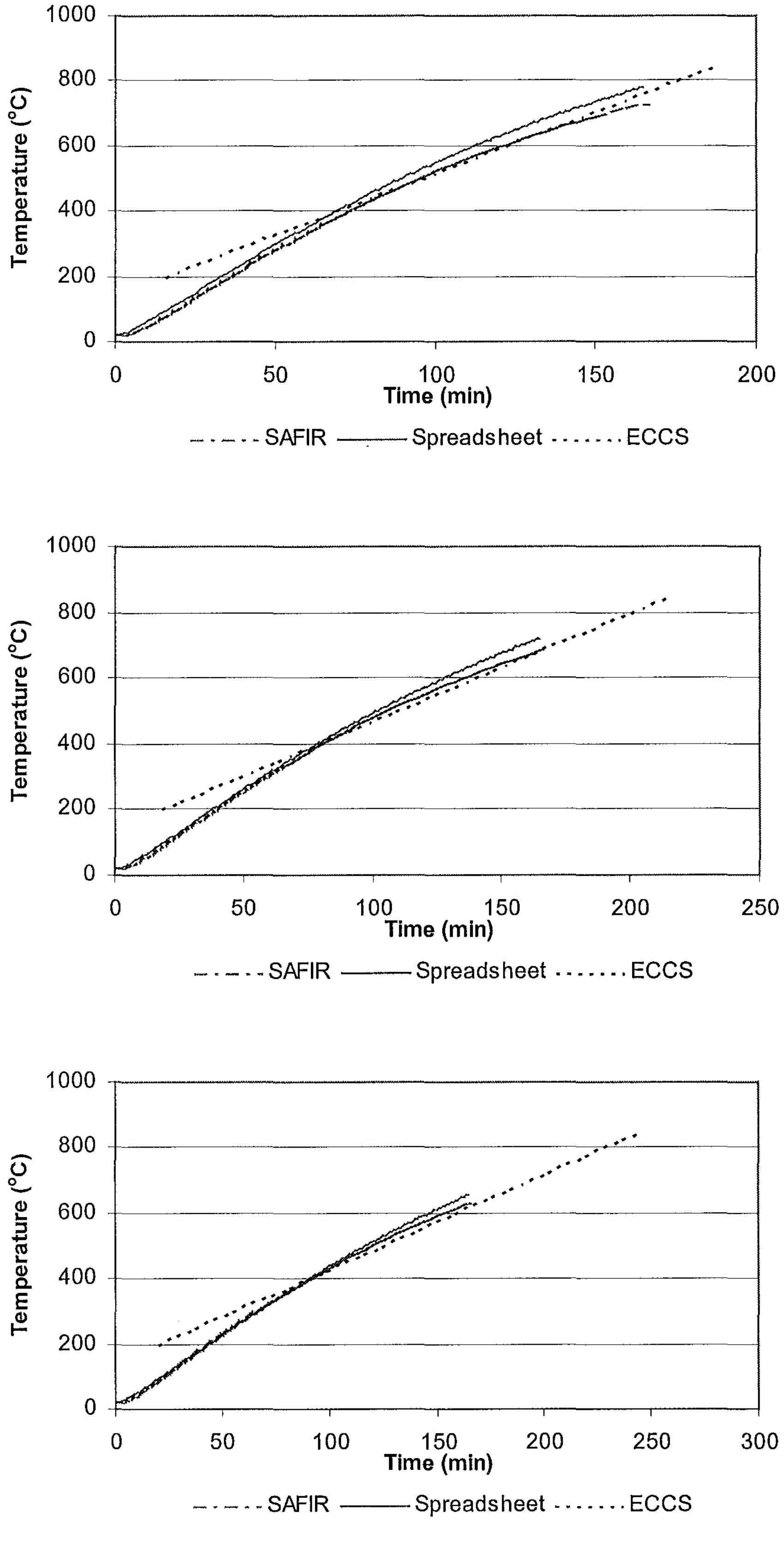


Figure 5.10 a-c: Comparison between results from the spreadsheet method with the results from SAFIR and with the ECCS equations for protected steel members with heavy thick protection. From top to bottom: a. 180 UB 16, b. 310 UB 40.4 and c.530 UB 82.0

From Figure 5.10 a-c, the ECCS equations give good results again with the average steel temperatures found from the results of SAFIR simulations and spreadsheet analyses. The upper temperature limitation again can be increased to 800 °C, and linear interpolation below 400 °C would give accurate results. The time and beam size limitations do not appear to be relevant in this analyses which supports the conclusions stated in Sections 5.2.3 and 5.3.2.

The average SAFIR temperature is always slightly cooler than the temperature from the spreadsheet calculations as is also seen in Figure 5.9. The effect of the thicker protection is to distribute the energy conducted to the steel more evenly and at a slower rate. This means that conduction through the steel section more actively reduces the variation of temperature across the cross section. In the spreadsheet method conduction is not considered because the one dimensional heat flow model that the formulas are based on give a uniform thickness and energy flow to the steel.

5.6 RESULTS FOR THREE SIDED EXPOSURE WITH HEAVY PROTECTION:

Protected beams with three sided exposure usually occurs when a concrete slab is being supported by a steel beam, and the other three faces are protected with insulation. In this section this is the only case considered, as the cases where insulation is applied to the top face and three sided exposure still occurs is unlikely. This approach gives lower temperatures than if insulation was applied to the top face, but as seen in Section 4.3.1 and Figure 4.10, the maximum temperature of the steel section is unaffected by the introduction of a concrete slab rather than insulation to the top face. For this reason this simplification in comparing methods has been taken.

The properties of the insulation applied to the steel section are those of Fendolite by Firepro Safety Ltd, also used in Section 5.2, with constant values taken as below:

Specific heat, $c_i = 1100$ J/kg K

Thermal conductivity, $k_i = 0.19$ W/m K

Density, $\rho_i = 775$ kg/m^3

Thickness, $d_i = 0.02$ m

5.6.1 Results from a Simulation with the SAFIR Programme:

When analysing the unprotected steel sections with a concrete slab on the top flange, the wizard pre processor was used to set up the data and structural files required by SAFIR for the simulation. However, difficulties were experienced when this was attempted with protected steel. To overcome this problem and attempt to model the effect of having a concrete slab supported by the steel beam, the pre processor by John Mason was used. This pre-processor does not have the option of having a slab on top of the beam, but by protecting the beam with spray on protection on four sides, and then changing the properties of the protection to those of concrete for the elements on the top face of the beam, a concrete slab can be modelled.

The problems with this method is that the thickness of the concrete slab is 20 mm rather than 150 mm, and the width of the concrete slab only extrudes to the edge of the insulation, or 20 mm further on either side of the width of the beam. Making the assumption that this models the effect of a concrete slab is conservative as using a thicker slab that extrudes further from the faces than shown here will give lower temperatures than those found using this method.

Figure 5.11 shows the layout of the protected steel beam as inserted into SAFIR, and the resulting contour lines of temperature after 10 minutes of exposure to the ISO 834 fire.

In Figure 5.11, the contour lines can be seen to follow the perimeter of the beam through the insulation, but not through the concrete slab. This is because there is no fire exposed to the outer face of the concrete slab. The temperature of the slab increases due to conduction from the steel, but the temperature of the concrete is much lower than that of the insulation and the steel. The temperature of the coolest contour line is 84 °C but this is at the steel-insulation interface. It can be seen from Figure 5.11 that this contour does not extend around to the concrete-steel interface even though the temperature of the flange is close to 84 °C. The temperature of the nodes at the steel concrete interface along the top flange range from 58 °C to 60 °C at this time, which is significantly lower than that of the equivalent nodes on the bottom flange which at are temperatures between 110 °C and 120 °C.

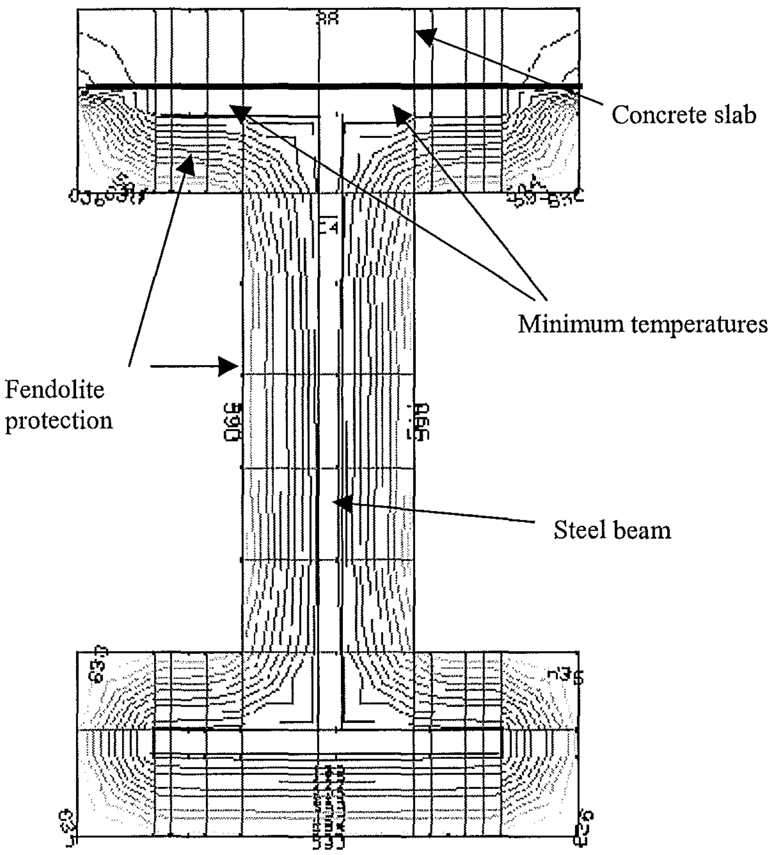


Figure 5.11: Temperature contour lines for a 180UB16.1 beam protected with Fendolite and with a 20 mm concrete slab, exposed to the ISO 834 fire on three sides.

The temperature variation across the cross section is shown below in Figure 5.12. The maximum temperatures occur through the web and the lower flange and the minimum temperatures occur midway along the flange overhang, as shown in Figure 5.11

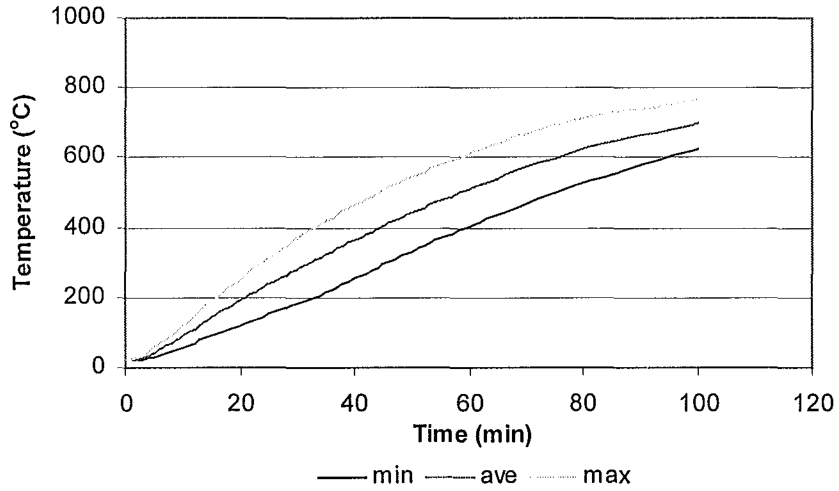


Figure 5.12: Variation of maximum and minimum temperatures from a simulation in SAFIR for a 180 UB 16.1 beam with heavy protection and a concrete slab.

The maximum and minimum temperatures vary greatly across the cross section as shown in Figure 5.12. The maximum temperature difference between the maximum and minimum temperatures is over 200 °C, and the difference appears to have reached a constant value. The variation between the maximum and minimum temperature is much more marked due to the concrete slab in place, which absorbs heat energy from the steel and subsequently cools the top flange. The maximum temperatures located in the web and the lower flange is not affected by the presence of the concrete slab. When comparisons are made with four sided exposure as stated in Section 4.3.1, the maximum and therefore the likely limiting temperature of the concrete slab does not change with between four or three sided exposure conditions.

5.6.2 Heavily Protected Beams with Three Sided Exposure:

Three sided exposure is modelled in SAFIR as explained in Section 5.6.1, and the results from these simulations are compared with results from calculations made by the spreadsheet method in this section. The ISO 834 fire is subjected to the steel section on the three sides that are protected with insulation, while the fourth side is left at ambient temperatures to represent the effect of having a concrete slab with a top surface in a different compartment, not experiencing elevated temperatures.

The spreadsheet results are from calculations using a reduced section factor as used with unprotected steel, refer to Section 1.6.3 for more detail in the calculation of the section factor. The results are shown in Figure 5.13 for the 180 UB 16.1, which gives typical results for the three beam sizes analysed.

The spreadsheet method aims to give the average temperature of the steel, whether protected or unprotected. From Figure 5.13, however, the results from calculation made by the spreadsheet method give temperatures closer to the maximum temperatures found in SAFIR. Although the temperatures found by the spreadsheet method differ substantially from the average temperature found by the SAFIR results, this is due to the variation in temperatures found from the SAFIR simulations with three sided exposure from cooling effects of the concrete slab that is not seen with four sided exposure as in Figure 5.1.

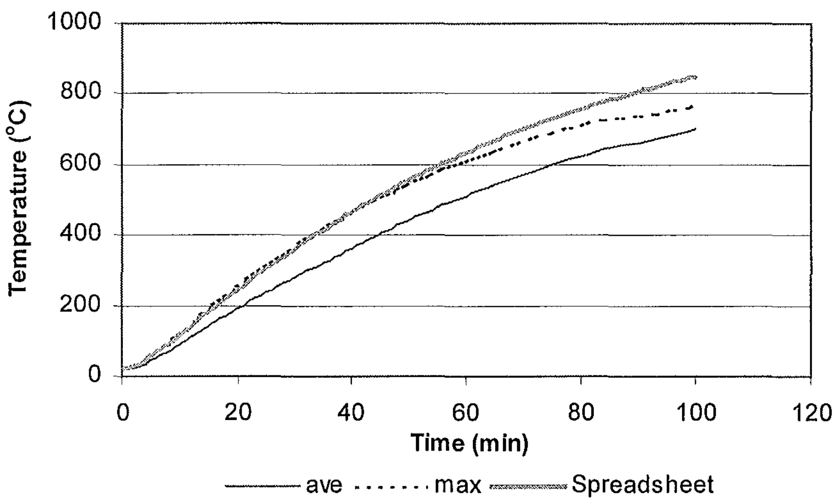


Figure 5.13: Comparison between maximum and average temperatures found from the SAFIR programme with the results from the spreadsheet calculations for a 180UB16.1 beam exposed to an ISO fire on three sides.

The maximum temperatures found from the SAFIR results with three sided exposure as seen in Figure 5.13 are the same as the maximum temperatures found for four sided exposure. This is because the lower flange and web are unaffected by the concrete slab which cools the top flange and therefore lowers the average temperature of the beam. The spreadsheet method does not model any effects of the slab except to reduce the section factor for a reduced heated perimeter. Reducing the section factor in effect increases the effective width, making the temperature rise of the steel decrease to a slower rate. The difference is very small however so a substantial difference in the temperature results from the spreadsheet method is hard to distinguish when comparisons are made between the spreadsheet method and SAFIR.

The maximum temperatures found in the beam are not affected by changing the fire exposure conditions. For conservative results for the temperatures reached in the member, analysis of the member as if exposed on four sides to the fire by the spreadsheet method gives results close to the maximum temperatures as found by the SAFIR programme. Even though the average temperature is much lower when a concrete slab is present as found in SAFIR, this only because a small percentage of elements are at a much cooler temperature which subsequently lowers the average temperature of the steel. Throughout the section of the steel however, only the cooling effects of the concrete affect the top flange that is in contact with the slab. Since it is the lower flange that yields and forms a plastic hinge, this cooling effect does not affect the failure temperature of the beam.

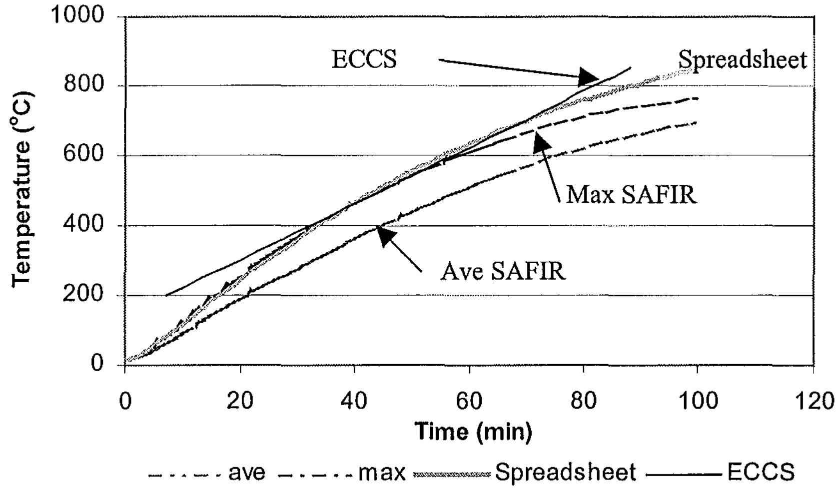
5.6.3 Comparison with the ECCS Formula:

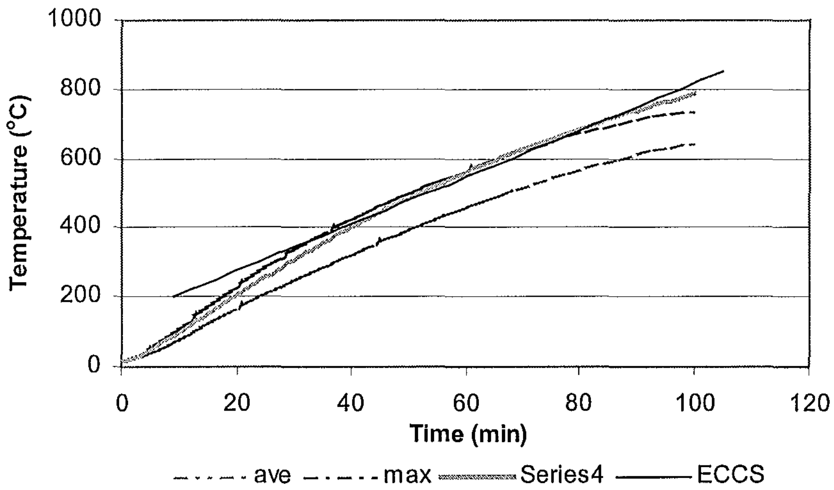
The ECCS equations for three sided exposure are the same as for four sided exposure but with a reduced section factor. The equation for protected steel beams with heavy insulation is equation 5.1 in Section 5.2.3, and is below:

$$t = 40(T_l - 140)\left[\left(\frac{d_i}{k_i}\right)\left(\frac{A}{H_p} + \frac{c_i \rho_i d_i}{2 c_s \rho_s}\right)\right]^{0.77}$$

The properties of the insulation are listed in Section 5.6, and are of Fendolite by Firepro.

Figure 5.14 shows the comparison of the ECCS formulas with three sided exposure compared with the results from the spreadsheet method and SAFIR.





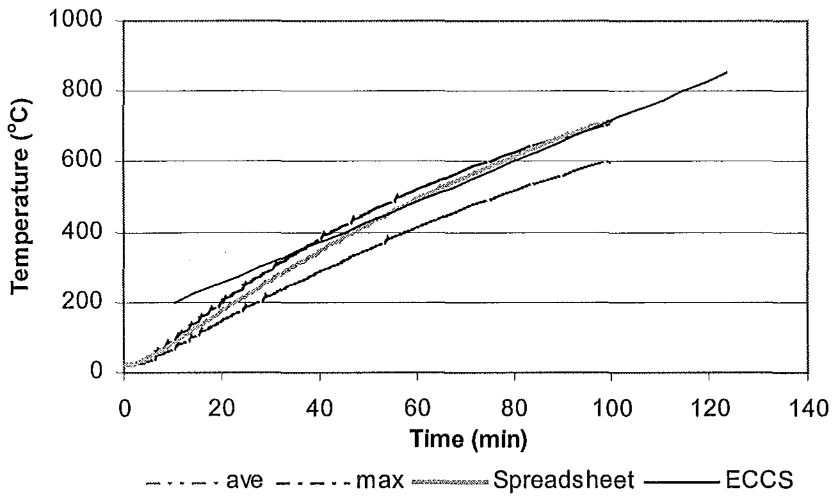


Figure 5.14: Comparison between the results from SAFIR and the spreadsheet method with the ECCS equation for protected steel members with three sided exposure to the ISO 834 fire. From top to bottom a. 180 UB 16, b. 310 UB 40.4 and c.530 UB 82.0

Figure 5.14 shows the correlation between the ECCS recommended formulas with the time-temperature curve resulting from the spreadsheet method and the maximum and average temperatures found from simulations in SAFIR. The graphs show that the straight lines fit well with the spreadsheet results, and also with the maximum temperatures from SAFIR. The curves do not fit well with the average temperature from SAFIR.

As with earlier discussions about the ECCS equations, the limitations on the temperature range that these equations are valid can be adjusted. Linear interpolation below 400 °C will give accurate estimations of time-temperature points, and the upper temperature limit could be extended to 800 °C. Due to the slow heating found in this simulation, not all three beams have reached this temperature in the time period simulated. Figure 5.14 a and b, however, justify this upper limit, and by extending the curves in Figure 5.14 c, the curves will be close at this temperature also.

The other limitations imposed on this equation regarding the times that this equation is valid for, and the beam size do not affect the accuracy of the equation and do not appear necessary.

5.7 COMPARISONS WITH FIRECALC:

5.7.1 Heavily Protected Beam with Three Sided Exposure:

In this section the results from the spreadsheet method is compared with the results given by the Firecalc programme. The spreadsheet results are used in place of the results from the SAFIR finite element programme due to the methods of temperature evaluation made in Firecalc. The data entered into the analysis programme is very similar to the variables in the formulas in the spreadsheet method, and the output is in the form of the average temperature.

The output from the Firecalc programme gives the fire temperature, the insulation surface temperature and the steel temperature, as well as the load bearing capacity. See Section 2.3.2 for more detail on the analysis procedure of Firecalc.

The properties of the protection applied to the beam in Firecalc are those of Fendolite protection by Firepro, see Section 5.2 for these properties. Firecalc has an option to give the moisture content of the insulation which SAFIR does not include. For the purposes of this report, the moisture content of Fendolite has been taken as zero to provide consistency between the results. The spreadsheet method can cater for the effect of a high moisture content in the insulation by adding a time delay term at 100 °C when the moisture in the insulation would be evaporated.

The results from an analysis with the Firecalc programme gives the results in Figure 5.15

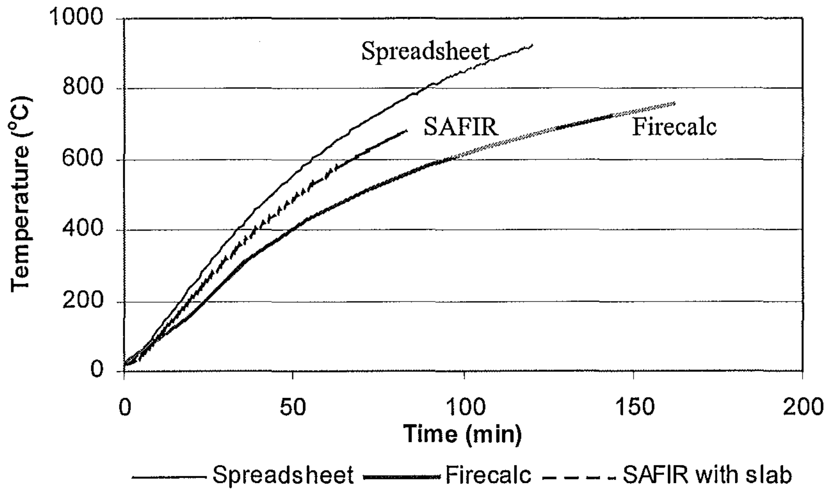


Figure 5.15: Comparison between results from Firecalc, SAFIR and the Spreadsheet method for a 180UB16.1 beam with 20 mm heavy protection.

From Figure 5.15 the temperatures from the Firecalc programme are consistently lower than those found from the spreadsheet method. The Firecalc programme gives lower temperatures for this protection case, and if the moisture content had been added as a feature, this would have an even bigger deviation from the temperatures from the spreadsheet method. The spreadsheet does not model the effects of a concrete slab, but when comparing the results from Firecalc with those of SAFIR with a concrete slab, the temperatures from Firecalc are still too low. As in Section 4.4.2, the properties of the concrete in the Firecalc programme are unknown but it is assumed they are not significantly different from the properties in SAFIR.

5.8 CONCLUSIONS:

The thermal behaviour of protected steel members has been examined in this section. In the New Zealand code at present there are no formulas available to aid designers in the estimation of the temperature of protected steel members. The equations recommended by ECCS relate closely to the results found from the spreadsheet method and SAFIR.

The empirical equations used in this section from ECCS give good results when compared with the time-temperature curves resulting from SAFIR simulations. As in Section 4, the upper temperature limit can be increased to allow more use to be made of these equations. The upper temperature value for protected steel can be increased to 800 °C and remain within the same accuracy as the line within the present temperature range criterion. The other limitations imposed on the steel member regarding the time and beam sizes for which the equation is valid do not seem to be a factor in the accuracy of the equations. The limitation regarding the thickness and thermal conductivity of the insulation has not been discussed because all tests examined in this report have complied with the range suggested for the equations.

The original form of the equation is intended for use of steel beams protected with 'light' insulation, but for 'heavy' insulation there is a modified formula, which accounts for the thermal capacity of the insulation. This formula only applies well for four sided exposure with protected members, and although the equation compares well with results from the spreadsheet method for three sided exposure, this is rather conservative as the spreadsheet method assumes a smaller amount of protection applied with its smaller section factor. When considered that most three sided exposure results from conditions with a concrete slab overlaying a steel beam, this equation gives a time-temperature relationship which is high for three sided exposure.

The formula does works well for four sided exposure and is a useful tool and a simple alternative to the present guide in the New Zealand code to use data from experimental tests. The formula gives accurate results for light and heavy insulation.

Heavy and light protection has been considered in this section, and the assumptions as to the simplified approach for light protection used in the spreadsheet method equations and in the ECCS equations appear valid. When the heat capacity of the insulation is neglected the temperatures are higher than when it is considered, but within the accuracy that can be expected for these results.

For boxed protection, the spreadsheet analysis gave good results that were slightly higher than the time-temperature curves plotted from SAFIR results. The radiative and convective components of heat transfer are not considered in the spreadsheet, but are in the SAFIR programme. The addition of these extra heat transfer properties account for the spreadsheet assuming that the insulation is in contact with all sides of the beam.

Thicker insulation has also been examined in this section for heavy protection. The results of this comparison show that the spreadsheet gives good results for protection thickness of at least up to 40 mm.

6 COMPARISON OF METHODS USING OTHER FIRE CURVES:

6.1 INTRODUCTION:

To ensure that the results found by comparing methods of calculating the thermal response of steel beams exposed to the ISO 834 fire gives reasonable and accurate results, the same comparisons have been repeated with other fire curves. As described in Section 2.4.2, there are five Eurocode Parametric curves being studied in this report with varying fuel loads and ventilation factors and a constant wall lining value. These variations are to provide a range of fires and demonstrate that the methods here can be applied to many cases. Since each parametric curve is different, only one beam size has been used in this section to reduce the repetitiveness of the results and reduce the time to analyse the same procedure many times. Real fire experimental data has also been used to verify the thermal response methods used in this report.

6.2 EUROCODE PARAMETRIC FIRES:

6.2.1 Introduction:

The Eurocode Parametric curves are more realistic curves than the ISO 834 fire as the temperature depends on the ventilation, the fuel load present and the thermal properties of the wall linings of the compartment. The duration of heating of the parametric curve is dependent on the amount of fuel available and it has a decay phase that occurs after the peak, which is also dependent on the fuel load and ventilation of the room.

The SAFIR pre-processor developed by John Mason has a function allowing different fires to be analysed with the SAFIR programme that could not be analysed before. The Eurocode Parametric fire is one of these, and by entering appropriate values for the opening factor, wall lining properties and fuel load the fire can be defined.

6.2.2 Assumptions:

When using the Eurocode fire formula, the value for $\sqrt{k\rho c}$ of the wall linings is used, not the individual components of the factor. When inputting data into the SAFIR , values for each component were required to be entered. To achieve a value of 1160 for $\sqrt{k\rho c}$, values of k, ρ and c were adjusted to get an exact value of 1160 for the square root of the product of the three thermal properties. The other assumptions as stated in Section 4 and 5 referring to the temperature of the surrounding air and constant temperature throughout the cross section of the beam are valid in this section also.

The pre-processor displays the information concerning the fire such as the time to peak temperature, peak temperature and decay rate and these corresponded with those calculated for the spreadsheet analysis for all parametric fires used in this report.

The Eurocode fires were simulated in the SAFIR programme with only one beam size to reduce the number of iterations performed. This beam is the BHP 310-UB-40.4, and is the medium sized beam that was used in the ISO standard fire comparisons. It is assumed that the results that are found in this section with this beam will provide the same conclusions as with other sized beams. The results found in Sections 4 and 5 suggest that the analysis of one beam size is relevant, and the method transferable to other beam sizes.

6.2.3 Results for unprotected steel exposed to the Eurocode Parametric fire:

A comparison between the spreadsheet method and the results from the SAFIR analysis show that the spreadsheet method can be an effective and accurate way to model the behaviour of unprotected steel for both heating and cooling stages of a real fire.

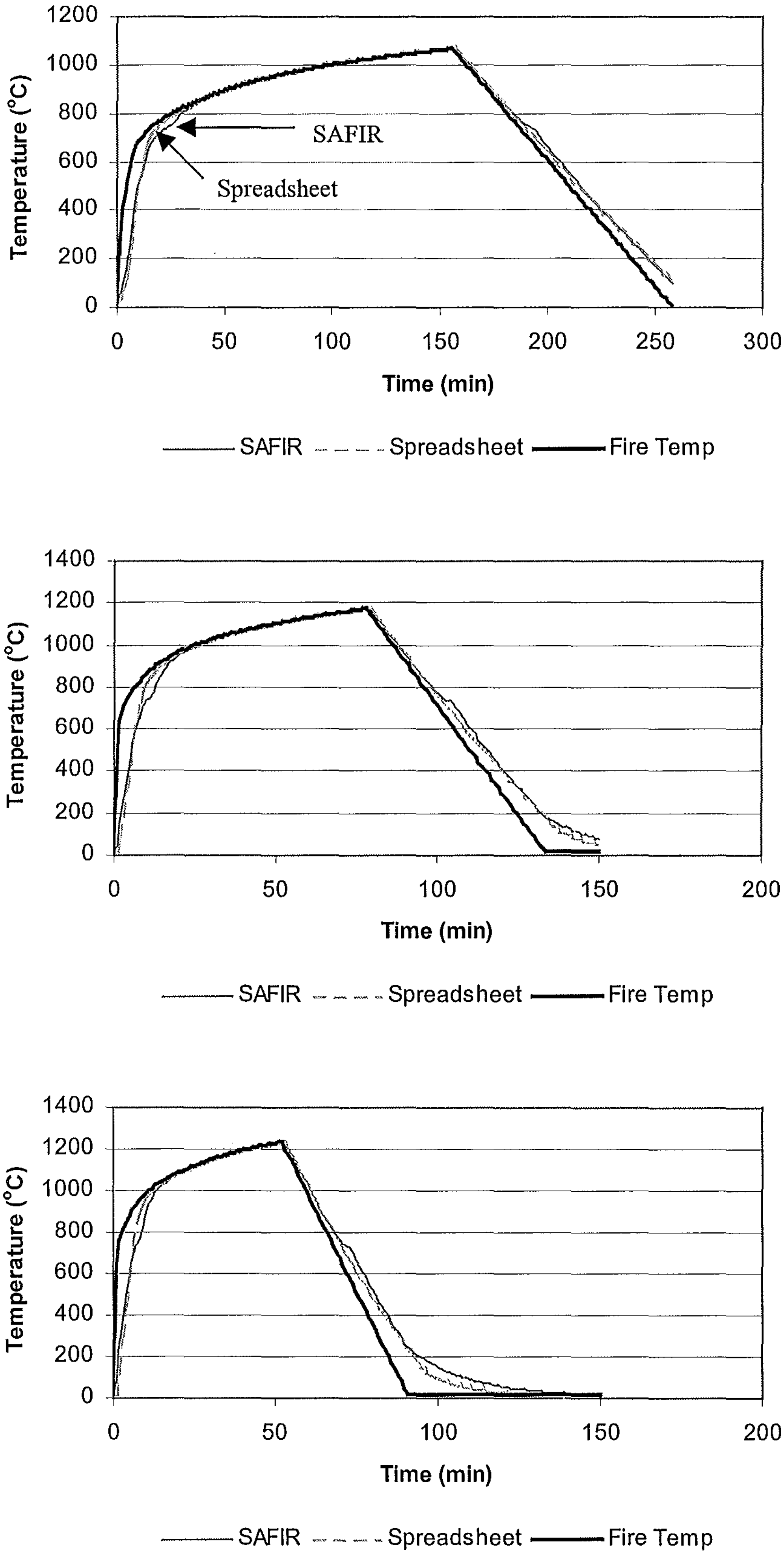


Figure 6.1 a-c: Comparison between SAFIR and spreadsheet results for an unprotected steel beam with four sided exposure to a parametric fire, from top to bottom: a. 0.04-800, b. 0.08-800 c.0.12-800 fires

This time-temperature curve shows the results from the spreadsheet method and the SAFIR programme. The curve of the fire is also shown, which remains at 20 °C once the fire decays to this temperature. This Eurocode parametric fire has a ventilation factor of 0.04,0.08 and 0.12 from top to bottom respectively; a fuel load of 800; and a thermal capacity of wall linings ($\sqrt{k\rho c}$) of 1160. See Section 2.3.2 for more details regarding the Eurocode fires.

Figure 6.1a-c shows that the temperatures of the steel from both the SAFIR simulation and the spreadsheet analysis reach a temperature close to the temperature of the fire and that the temperature of the steel begins to decrease immediately after the temperature of the fire begins to decay. At the peak fire temperature, the steel temperature is less than 2 °C lower than the fire. The rate of temperature decrease is slower in the steel than the rate of decrease of the fire because the temperature decrease is based on the difference of temperatures. When the temperature difference between the fire and the steel is small, the decreasing rate of temperature of the steel is small because the steel can not lose as much heat energy to its surroundings if the surroundings are at a similar temperature.

As in Section 4 and 5 with the ISO fire, the curve from the SAFIR analysis reaches a plateau when the temperature is around 650 –750 °C. The curve from the spreadsheet calculations continues with a steady increase of temperature, until the steel temperature nears the temperature of the fire. This occurs during the decay region also when the steel is cooling down. This is due to the specific heat of steel changing in the SAFIR programme, and remaining constant in the spreadsheet analysis. As with the heating of the steel, when the beam can absorb more energy before the temperature increases, when the steel temperature is between 650 – 800 °C, the steel must lose more heat energy before it can cool down in this temperature range.

Figure 6.1 a-c confirms the results seen with the ISO fire in Section 4, that the spreadsheet method gives very close results to those found in SAFIR for unprotected steel with four sided exposure.

6.2.4 Results for protected steel:

The insulative protection used in this section is *Fendolite* and is also used in Section 5.2 and 5.5. The properties of this protection are as follows:

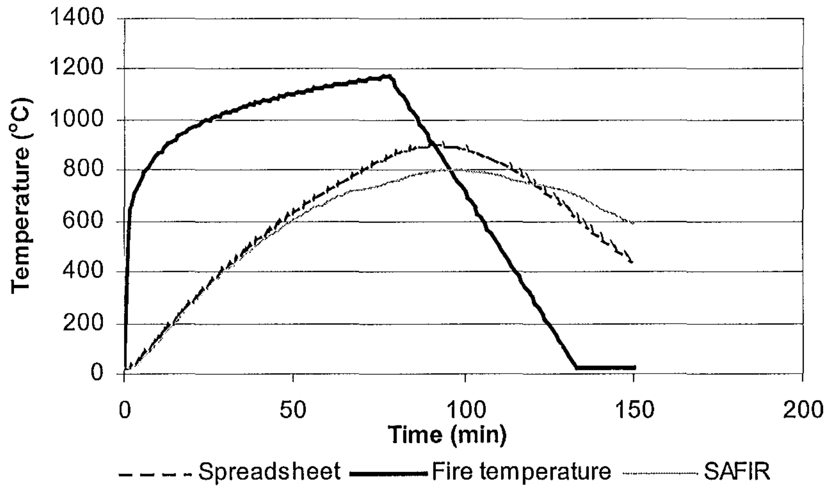
Properties of spray on protection: Fendolite by Firepro

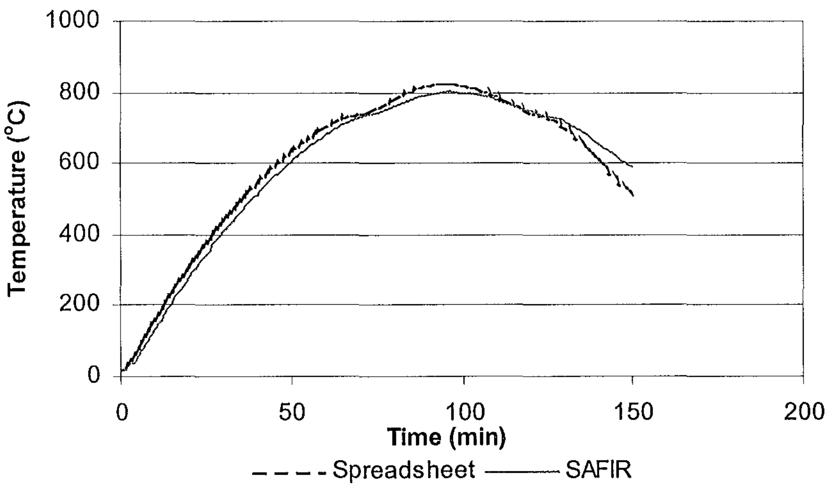
Specific heat, $c_i = 1100$ J/kg K

Thermal conductivity, $k_i = 0.19$ W/m K

Density, $\rho = 775$ kg/m^3

Thickness, $d_i = 0.02$ m





Figures 6.2 a-b: Comparison between the results from SAFIR and the spreadsheet method for protected steel exposed to a Eurocode parametric fire. From top a. with constant specific heat in spreadsheet method, b. with varying specific heat with spreadsheet method

Protected steel exposed to the Eurocode parametric fire gives similar results to the results found from the comparisons with beams exposed to the standard ISO 834 fire. The results from the spreadsheet give higher temperatures than the results from the SAFIR programme as with the results with the ISO fire. The curve with results from the spreadsheet method allows for the heat capacity of the insulation due to the properties of the insulation being classed 'heavy'.

This Eurocode parametric fire has a ventilation factor of 0.08, a fuel load of 800 MJ/m^2, and a thermal inertia of the wall linings of 1160 $Ws^{1/2}/m^2$ K and is the 'middle' fire of those used in this report. The beam is the medium weight beam used throughout this report and sized as BHP 310 UB 40.4.

Figures 6.2 a, the spreadsheet curve and SAFIR curve follow the same path until the temperature reaches about 650 °C, at a time of about 45 minutes. The spreadsheet then gives lower temperatures than the SAFIR programme. The lower temperatures from SAFIR after the steel reaches a temperature of 650 °C is due to the higher specific heat of steel which is taken into account by SAFIR but not in the spreadsheet method. The slower decrease in temperature in the decay stage of the fire is due to the same effect.

The temperature difference between the two methods is more pronounced in protected steel than unprotected steel due to the time period that the steel is in the 650 – 800 °C temperature range. Since the steel is heating up at a slower rate with protected steel than with unprotected steel, the time that the steel is in this temperature range is longer and the results from the spreadsheet method deviate further from the SAFIR temperatures in these situations.

The results from the spreadsheet turn out to be quite conservative because it estimates higher temperatures due to this effect and the maximum temperature reached in the beam from the spreadsheet method is 901 °C while the maximum temperature found from SAFIR is 800 °C. The difference of slightly more than 100 °C, means the spreadsheet has a maximum temperature of 12.5 % more than that found from using the SAFIR simulation.

Figures 6.2 b shows the comparison of the results from the spreadsheet method with those from SAFIR. The curves are much closer to each other than those in Figures 6.2a when the changing specific heat of steel is not taken into account by the spreadsheet method. The maximum temperature reached in the modified spreadsheet analysis is 825 °C, which is only 25 °C higher than the maximum temperature reached from the SAFIR simulation.

The decay region of the simulation in Figures 6.2 a and b shows differences between the results from SAFIR and the spreadsheet method. In Figures 6.2 a this can be explained by the differences in specific heat, but Figures 6.2 b should have a closer decay rate than that that appears on the graph. The rate of temperature increase is very similar in Figures 6.2 b, so it is expected that the rate of decrease should be more similar also. The SAFIR curve appears to be slightly translated to the right from the spreadsheet method curve, which suggests that the steel from the SAFIR simulation takes longer before it begins to heat up. The rate of decrease from the SAFIR simulation is quite substantially slower than the decrease rate with the spreadsheet method, so the steel is losing heat to its surroundings more slowly than the spreadsheet method suggests.

The SAFIR programme also has variations of specific heat, density and thermal conductivity for its insulation. This could contribute to the difference in the results, although it does not explain why the difference occurs only in the decay stage and not in the heating stage at temperatures below 700 °C.

6.3 REAL FIRES:

To confirm the results and conclusions found in Sections 4 and 5 of this report, the temperatures of steel beams and fires from experimental test data has been compared with calculations performed by the spreadsheet method, and simulations in SAFIR with the same fire temperature data. The beam sizes used in the unprotected and protected tests have been used in the computer analysis where possible, and where not the closest beam size by dimensions and mass per unit length has been used.

6.3.1 Unprotected Steel:

The experimental data comes from a 'Compendium of UK Standard Fire Test Data, Unprotected Structural Steel – 1' (Wainman and Kirby, 1988). The beam is sized according to British Standards, and is a 203 x 133 mm beam, with mass of 30 kg/m length. The steel temperatures from the experimental data is measured at four locations on top flange, four locations on the web, and five locations on the lower flange. The beam was exposed to an ISO 834 fire and the mean furnace gas temperature is recorded. All temperatures have been measured at three minute intervals.

The beam has a 132 mm concrete slab protecting the top flange, resulting in three sided exposure conditions for the beam. To perform simulations in SAFIR with a concrete slab, the pre-processor wizard developed by Ionica and Vanderseipan, must be used because the pre-processor developed by John Mason does not have these capabilities, see Section 2.3.1. The elevated temperature conditions were exposed to three sides of the beam and to the under side of the concrete slab.

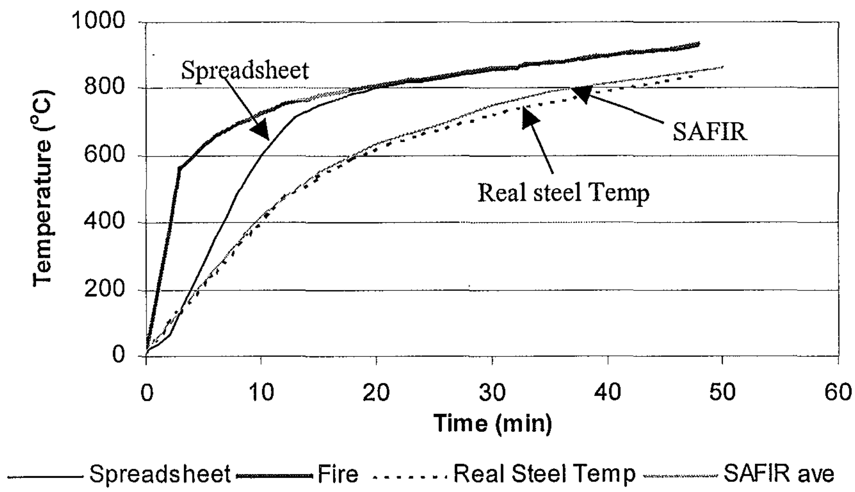


Figure 6.3: Comparison between the average temperature from experimental data for three sided unprotected steel with results from the spreadsheet method and average temperature of a SAFIR simulation

The average temperature for the top and lower flange, and the web are shown in Figure 6.3. This figure also shows the results from a calculation by the spreadsheet method and from the simulation in SAFIR using the same sized beam and exposure conditions.

Figure 6.3 a shows that the average temperature of the unprotected steel member as tested by Wainman and Kirby, (1988), gives results very close to the average temperature predicted by SAFIR. The results from the spreadsheet method are significantly higher than the average temperature reached in SAFIR and the test data. The spreadsheet does not consider the cooling effects of the concrete slab on top of the beam however, and differs from four sided exposure by the reduced section factor only.

Although the concrete slab cools the top flange significantly by absorbing heat from the flange and consequently cooling it, the bottom flange is not affected by the presence of the slab. Failure can still occur when the top flange is relatively cool if the bottom flange and web is too hot. Figure 6.4 b below shows the comparison between the maximum temperatures reached in SAFIR with the temperatures measured in the bottom flange in the experimental data from the same beam and test mentioned above.

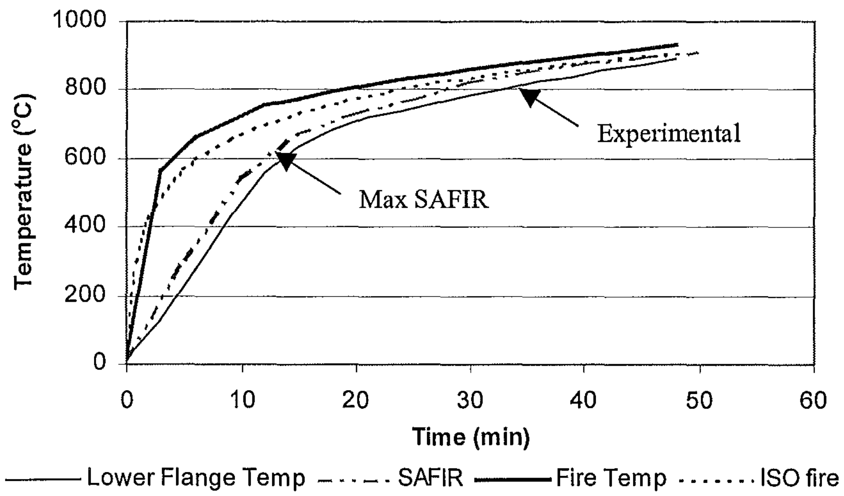


Figure 6.4: Comparison between the temperature results measured from an experimental fire test with the maximum temperatures found from a SAFIR simulation, and temperatures from the spreadsheet method.

From Figure 6.4, the maximum temperature from the SAFIR simulation is slightly higher throughout the test than the temperature in the lower flange of the beam measured in the experimental data. The maximum temperatures of the steel beam with this construction are found in the web during the early stages of the test, but the lower flange and web tend to the same temperatures as the fire progresses. The top of the web is slightly cooler than the rest of the cross section of the member due to the top flange being cooled by the concrete slab, and as a result slightly cooling the top of the web.

Although in Figure 6.3, the results from the spreadsheet method were significantly higher than the temperatures from the experimental data and from SAFIR, in Figure 6.4 the temperatures from the spreadsheet method at the later stages of the fire correspond well with those from these other sources. After around 30 minutes the spreadsheet and the maximum temperatures from SAFIR and the experiment give temperatures with small error. This suggests that the spreadsheet method will give designers a good indication of the maximum temperatures of the steel because the time frame that designers are concerned with are generally at least 30 minutes and longer.

For a limiting temperature of around 600 °C however, the time to reach this temperature is significantly faster with the spreadsheet method than found from the experimental data and SAFIR. These results from the spreadsheet method are therefore a bit too conservative and too low.

6.3.2 Protected Steel:

The experimental data for a protected member comes from 'Natural Fires in Large Scale Compartments', (Kirby et al 1994). The beam is sized according to British Steel Products, and is of dimensions 254 x 146 mm, and mass of 43 kg/m. The protection applied to the beam is Vicuclad© board protection by Promat Fire Protection. The insulation is applied to three sides of the steel beam, with a 50mm thick paving slab on the top flange to simulate the thermal effects of a concrete slab. Vicuclad is a vermiculite based product mixed with inorganic binders. The properties of this board are not included in Kirby et al, (1994), so the following assumptions have been made:

Density: 400 kg/m^3 (from Promat internet site)

Specific heat: 1100 J/kg K

Thermal conductivity: 0.15 W/m K (Buchanan, 1999)

The fire that the test beams were exposed to is based on the Eurocode Parametric Fires. The temperatures were achieved by burning wood cribs with a fuel load of 20 kg wood/m^2 floor area, and having a ventilation factor of ¼ of the end wall. The measurements recorded in Kirby, et al (1994), give the temperatures of the lower flange throughout of the test, and of the atmosphere at 300 mm below the roof, which is in line with the lower flange.

The calculations of the steel temperature by the spreadsheet method were made by substituting the temperature of the fire at time steps, and then calculating the steel temperature using this fire. The formula used is that used throughout this report, equation 2.5. Although this protection is box protection, no allowance is made for the radiation and convection between the inner surface of the insulation and the steel surface in the spreadsheet method, Refer to Section 5.4 for more information on boxed protection.

The simulation in SAFIR was made by entering the appropriate values for the parametric fire to obtain a curve that fit as close as possible to the real fire curve as seen above in Figure 6.5. The values for the fuel load density, ventilation factor and wall linings properties were found in Kirby et al, (1994), and then modified to obtain a curve that fit closely with the real fire curve.

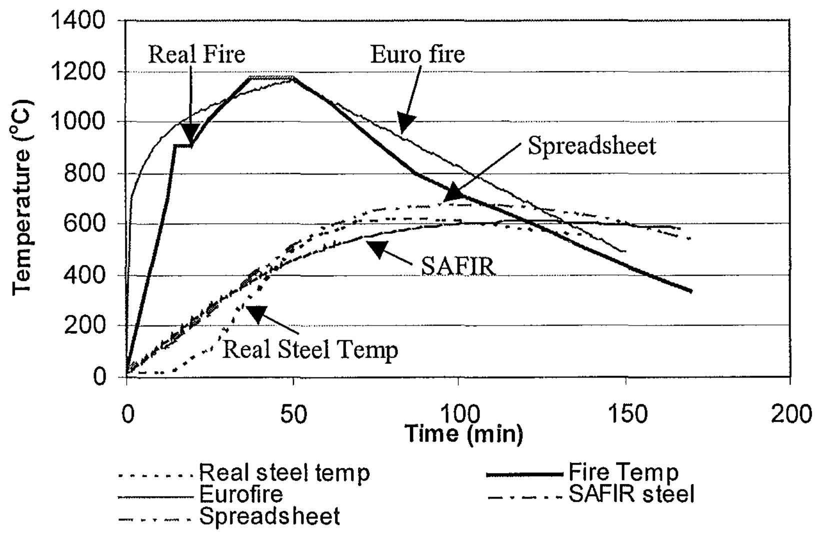


Figure 6.5: Comparison between the temperature results measured from an experimental fire test with the maximum temperatures found from a SAFIR simulation, and temperatures from the spreadsheet method for protected steel.

The fire data entered into the SAFIR programme for this fire are:

Fuel load density, e_f=320

Ventilation factor, F_v=0.05

Thermal properties of the wall linings, $\sqrt{k\rho c_p}$ =600

These values give an Eurocode fire with a heating time of 0.83 hours or 50 mins, a peak temperature of 1163 °C and a decay rate of 404 °C/hour, or 6.7 °C/min.

Figure 6.5 shows the comparison of the temperatures in the lower flange for protected steel as estimated by SAFIR and by the spreadsheet method with temperature results from experimental tests. The difference between the SAFIR results from the experimental results can be partly due to the difference in the fire curve as it was not possible to get an exact match of fire data. The temperature of the steel as predicted by SAFIR is higher than the experimental data, but the temperature of the fire it is simulated from is higher than the experimental fire. The maximum temperature reached in both curves is around the same but the peak occurs from the SAFIR results much later than was found in the experiment.

The steel temperature as predicted by the spreadsheet was achieved by entering the fire temperatures into the spreadsheet and adjusting the time step to fit the data points available. The results from the spreadsheet are higher than those from SAFIR and the experiment but as commented on in Sections 4.3 and 5.6, the spreadsheet method does not take into account the cooling effects of a concrete slab, and thus gives slightly higher temperatures than those found in SAFIR which can account for these effects.

7 ADDITIONAL MATERIAL IN EUROCODE 3:

7.1 INTRODUCTION:

The Eurocode documents contain a more in-depth description and guidelines on the structural design of steel elements for fire safety than the New Zealand Steel Code. Eurocode 3, ENV 1993-1-2 is the equivalent of Section 11 of NZS 3404, in Europe, but contains a lot more information for designers on the behaviour of steel and the prescribed methods for ensuring the elements will behave adequately in a fire situation.

This section of this report analyses what methods or descriptions Eurocode 3 contains in terms of fire safety that NZS 3404 does not, and contains recommendations for aspects of these to be added to the New Zealand Steel Code. Refer to Section 3 for an outline of the present New Zealand Steel Code. ENV 1993-1-2 is a large and quite cumbersome document, so a more concise and simplified version of the methods lacking from NZS 3404 would be better for the New Zealand Steel Code.

As seen in Section 3 of this report, the New Zealand Steel Code contains few theoretical methods for estimating the response of steel in elevated temperatures, beyond calculating the limiting temperature of steel and the time until this temperature is reached for unprotected steel. The other methods in NZS 3404 rely on data from standard fire experimental tests to validate and confirm the elements structural safety in fire conditions, which is not always convenient or possible to obtain. Presently, the New Zealand Steel Code concentrates on determining the Period of Structural Adequacy (PSA) of a member by calculating the temperature at which the member will fail when exposed to a fire, and subsequently the time when this temperature is reached can be estimated.

Eurocode 3 however, uses theoretical methods of calculating the PSA of a member by evaluating the strength of structural steel members at an elevated temperature. This is an evaluation of the strength of the member rather than an evaluation of the temperatures reached as recommended in the New Zealand Steel Code. These strength design actions are modified by factors that account for the variation of strength of steel with temperature, and decrease the nominal strength of an element.

There are a number of changes that can be made to improve Section 11 of NZS 3404 and these are outlined in this section of the report. Changes to the New Zealand Steel Code such as definitions and connection guidelines have not been covered in this report so are not commented on.

7.2 ANALYSIS OF THE EUROCODE:

7.2.1 Design Methods for Performance Requirements:

Eurocode 3 states the performance requirement that an element is to be 'designed and constructed in such a way that they maintain their required load bearing function during the relevant fire exposure'. Deformation criteria must be satisfied if the performance of the member relies on small deflection, ie. if the protection applied to the beam will not remain in place if there is too much deformation of the member.

The method in EC3, (1995) follows the principles of normal plastic design, but with modified loads for fire design and with reduced values of the modulus of elasticity and the yield stress of steel to allow for the loss of strength at these temperatures. This is to design structures to satisfy the strength criteria at elevated temperatures, while the New Zealand Steel Code predominantly suggests methods to establish the maximum temperatures reached in a member at elevated temperatures, and the time that this temperature occurs.

NZS 3404 makes a provision to allow for the design of members with reduced steel properties for fire design, see Section 3.1.1c. However, there are not detailed guidelines to assist designers in the use of this provision in the code, and the calculations made must be confirmed by an analysis method using experimental data. There are no methods recommended to satisfy this.

For thermal analysis in Eurocode 3, the thermal properties of steel are not modified by a safety factor as this is given a value of one, but the value of the particular property is modified for the effect of an increase of temperature of the steel. For strength and deformation properties for structural analysis, the safety factor is also unity, but the properties at ambient temperatures are modified by a 'reduction factor' which is dependent on the material temperature.

The assessment methods available for use by Eurocode 3, and the rules that they must satisfy are listed. The document then gives the analysis methods available for structural analysis and recommended to use. These are:

Global structural analysis

Analysis of portions of the structure

Member analysis

It is also stated that design may be based on the results of tests, and that to verify standard fire resistance requirements, a member analysis is sufficient.

Global Structure Analysis:

When a global structure analysis is carried out, the relevant failure mode from fire exposure, the temperature dependent material properties and the member stiffnesses must be taken into account.

It must then be verified that

$$E_{fi,d} \leq R_{fi,d,t} \qquad 7.1$$

Where $E_{fi,d}$ is the design effect of actions for the fire situation, including the effects of thermal expansions and deformations and $R_{fi,d,t}$ is the corresponding design resistance at elevated temperatures.

Global structural analysis considers the structure as a whole.

Analysis of portions of the structure:

Instead of analysing the whole structure by the global structural analysis method, a portion, or subassembly comprising appropriate portions of the structure may be carried out. Here the design actions at the boundaries of the subassembly may be obtained by a global structural analysis for normal temperature design by using:

$$E_{fi,d} = \eta_{fi} E_d \qquad 7.2$$

where E_d is the design value of the corresponding action for normal temperature design and η_{fi} is the reduction factor for the design load level for the fire situation given by:

$$\eta_{fi} = \frac{\gamma_{GA} G_k + \psi_{1,1} Q_{k,1}}{\gamma_G G_k + \psi_{Q,1} Q_{k,1}} \qquad 7.3$$

where $Q_{k,1}$ is the principal variable load, γ_{GA} is the partial factor for permanent actions in accidental design situations and $\psi_{1,1}$ is the combination factor for frequent values.

η_{fi} from Eurocode 3, is equivalent to the load factor r_f, from the New Zealand as this is the ratio of the loading on the structure or member with fire conditions to the loading on the structure for normal conditions. Equation 7.2, therefore, shows that the design resistance of a member when exposed to elevated temperatures from a fire, is a proportion of the resistance available in normal conditions based on the loading ratio between the two conditions.

Member analysis

Alternatively, individual members may be analysed for fire situations. For this analysis the restraint conditions at supports and ends of members; and the internal forces and moments at supports and ends are assumed to remain at the values calculated for normal temperatures throughout the fire test.

7.2.2 Structural fire Design:

Eurocode 3 gives complete design guidelines to follow when designing structural members to fire standards. These methods involve determining the fire loads enforced on a structure and analysing the strength of each member at elevated temperatures. The layout in this section follows that of Eurocode 3, and has also been based on the work of Buchanan, (1999).

To determine the performance of a steel member, analysis can be made of a single member, or of the structure as a whole, or more complex member arrangement with the use of a finite element computer package. This section details the design method of evaluating single members according to Eurocode 3. This analysis method may be used for single, simply supported members exposed to elevated temperatures.

General:

As stated earlier for global analysis, the load bearing function of a steel member shall also be assumed to be adequate if:

$$E_{fi,d} \leq R_{fi,d,t}$$

The design resistance $R_{fi,d,t}$ at time t shall be determined for the temperature distribution in the cross section by modifying the design resistance for normal temperature design to take account of the mechanical properties of steel at elevated temperatures. The design force may be axial force, bending moment or shear force either separately or in combination.

Tension members:

For tension members with uniform temperature distribution across the cross section, the design resistance N_f is given by:

$$N_f = Af_y k_{y,T} \qquad 7.4$$

where A is the area of the cross section, f_y is the yield strength at time t = 0, and $k_{y,t}$ is the reduction factor for yield strength at temperature, T.

If there is a non-uniform temperature distribution, the design resistance N_f may be determined from:

$$N_f = \sum_{i=1,n} A_i k_{y,T,i} f_y \qquad 7.5$$

Where A_i is the elemental area of the cross section, $k_{y,T,i}$ is the reduction factor for yield strength at temperature T of the element.

Alternatively, for a conservative estimate of design resistance for a tension member with non-uniform temperature distribution, equation 7.4 may be used by assuming the whole of the cross section is at the maximum steel temperature reached at time, *t*.

Compression Members:

Compression members are prone to buckling so the resistance to buckling of a steel member at elevated temperature must be evaluated. The design buckling resistance, $N_{b,fi,t}$, at time *t* of a compression member should be determined from:

$$N_{b,fi,t} = \chi_{fi}/1.2\, A k_{y,T,\max} f_y \qquad 7.6$$

where χ_{fi} is the reduction factor for flexural buckling in the fire design situation, and $k_{y,T,max}$ is the reduction factor for the yield strength of steel at the maximum steel temperature, T, reached at time t.

The constant, 1.2, is an empirical correction factor that allows for a number of effects including the strain at failure being different from the yield strain. The value of χ_{fi} is taken as the lesser of the values of χ_{fi} in the y and z axes.

Bending:

As with compression and tension members, the design of bending members depends on the temperature distribution across the cross section. For uniform temperature distribution, the design resistance of bending elements, M_f may be determined by:

$$M_f = S k_{y,T} f_y \qquad 7.7$$

where *S* is the plastic section modulus

For members with a temperature gradient over the cross section, the moment capacity of the member may be calculated from:

$$M_f = \sum_{i=1,n} A_i z_i k_{y,T,i} f_{y,i} \qquad 7.8$$

where z_i is the distance from the plastic neutral axis to the centroid of the elemental area, A_i.

The plastic neutral axis is located such that the elemental areas yielding in compression and tension on either side of the plane must be equal, such that

$$\sum_{i=1,n} A_i k_{y,T,i} f_y = 0 \qquad 7.9$$

An alternative method designing members with a temperature distribution across its cross section is to assume the member has a constant temperature profile, of the maximum temperature, and then increase its capacity depending on the fire exposure and member support conditions.

$$M_f = \frac{S k_{y,T} f_y}{\kappa_1 \kappa_2} \qquad 7.10$$

where κ_1 and κ_2 are adaptation factor for non-uniform temperatures across the cross section and along the beam, respectively.

These have values of:

$\kappa_1 = 1.0$	for a beam exposed on four sides
$\kappa_1 = 0.7$	for a beam exposed on three sides, with a composite or concrete slab on the fourth side
$\kappa_2 = 0.85$	at the supports of a statically indeterminate beam
$\kappa_2 = 1.0$	in all other cases.

Lateral Torsional Buckling of Members:

Buckling must also be considered for beams. Slender beams with no lateral restraint to the compression edge of the cross section are prone to buckling and can fail before the bending capacity of the beam is reached. If design of beams is limited to the flexural capacity of the member, then this can lead to the under design of members.

If the non dimensional slenderness, which is the ratio of slenderness to Euler Slenderness, for the maximum temperature in the compression flange at time t does not exceed 0.4, no allowance needs to be made for lateral torsional buckling. Where the slenderness is greater than 0.4, the design buckling resistance moment at time t of a laterally unrestrained beam is determined by dividing the reduction factor for lateral torsional buckling, χ_{fi}, by a factor of 1.2, as was also used for compression members. In the New Zealand Steel Code, the lateral torsional buckling factor has the notation, α_s.

Shear:

Designing for shear for fire situations should be modified from that for normal situations by the variation of yield stress of steel. The modified formula has the following form:

$$V_f = \frac{k_{y,T} V_s}{\kappa_1 \kappa_2} \qquad 7.12$$

where κ_1 and κ_2 are as stated earlier for bending member and V_s is the design shear resistance for normal temperatures.

As covered in Section 7.2.2, the Eurocode has detailed methods for designing structural steel members for fire by considering fire as another 'load' on the structure. These equations would increase the use of unprotected steel in buildings as the members can be designed to withstand the maximum likely temperatures. The equations stated in this section are also listed in Buchanan, (1999), and would serve as an effective means as an alternative to protecting steel as the norm.

7.2.3 Thermal Analysis of Steel Members:

As stated in Section 3 of this report, the analysis methods to determine the time temperature relationship for protected and unprotected steel members in Eurocode 3 are timestep spreadsheet methods, as has been used throughout this report for comparisons with SAFIR. Refer to Section 2.1 for more details on the applications and applicability of these methods.

The method to determine the time-temperature relationship for unprotected steel is quite non conservative, as currently used in NZS 3404, as it gives times that are too short or temperatures that are too low. Sections 4.2.3 and 4.3.3 show the correlation between the lines and the curves as simulated from SAFIR and the timestep method.

It is therefore recommended that the spreadsheet equation method be entered into the New Zealand Steel Code as an alternative method for a more accurate time temperature curve for design. The equations in the spreadsheet method can be used with more realistic fires to provide designers with a likely response of the steel member, and with the current use of computers, there is no need to use the simple hand calculation methods that provide only an estimate of the time temperature relationship.

The spreadsheet equations for the timestep method used in this report for protected steel should also be included in the New Zealand Steel Code. Further research into the alternative time step results commented on in Section 5.7 could be made if the simple equation used in this report is not deemed satisfactory.

If engineers using NZS 3404 wish to use the results of standard fire furnace tests, the regression analysis method should still be available to them, but with the increased confidence in theoretical calculations for behaviour of steel in fire, these are not necessary and the use of theoretical calculations can allow more freedom when designing rather than being limited by the availability of data.

7.2.4 Mechanical Properties:

As stated in Section 3.1.2, the mechanical properties of steel differ from that of the New Zealand Steel Code, but it is beyond the scope of this project to determine which gives the most accurate variation of the yield stress and modulus of elasticity of steel with temperature. The Eurocode formulas give data points of these properties rather than a formula, and the limiting temperature where the values of these properties tend to zero is consistent. A possible change to the New Zealand Steel Code, which will give more technically correct information, is to modify the formulas included in the code for the mechanical properties of steel to tend to zero at the same temperature.

The limiting temperature is a direct rearrangement of the formula of proportion of yield stress remaining at elevated temperatures.

The variation of the mechanical properties of steel as given in the Eurocode do not vary significantly from that given in the New Zealand Code so an adoption of the Eurocode methods would be acceptable. Alternatively a modification to the linear equation given presently for the yield stress could be made to adjust the limiting temperature to equal that of the yield stress.

Stress-strain relationships of different grades of steel at elevated temperatures are included in an Annex of Eurocode 3, as are equations, which give the relationship between stress and strain at elevated temperatures. Although these would not be necessary in this detail in the New Zealand Steel Code, an addition of a graph such as Figure 3.4 would assist designers in understanding the behaviour of steel at elevated temperatures.

7.2.5 Thermal Properties:

Other material properties that are included in the Eurocode are equations giving the variation with temperature of thermal elongation of steel, specific heat of steel and thermal conductivity of steel. The equations for these properties are all stated and commented on earlier in this report in Section 1.6.2. For each thermal property of steel, the approximate variation or constant value to use for simplified cases is given.

These are: Specific Heat – 600 J/kg K

Thermal Elongation – $14 \times 10^{-6} (T_s - 20)$

Thermal Conductivity – 45 W/mK

These values of mechanical and thermal properties of steel are used in the calculations determining the temperature rise and the strength loss of the steel in a fire situation. As outlined in Section 3.1.4 and 3.1.5, the temperature rise of protected and unprotected steel beams is recommended to be found by time step spreadsheet methods. These properties are used for the calculations of steel temperature by this method.

The Eurocode 3 also has clauses to allow temperatures and strength calculations to be made by advanced calculation models, and methods, such as computer models.

These methods may be used to provide a realistic analysis of structures exposed to fire, and be based on fundamental physical behaviour in such a way as to lead to a reliable approximation of the expected behaviour of the relevant structural component under fire conditions.

These methods can be used to determine the temperature distribution within the members and the mechanical behaviour of the structure or part of it.

Presently there are no thermal properties included in the New Zealand Steel Code. For calculations for the temperature rise of steel by methods other than the empirical equations currently included, however these values are required. From the results seen in Sections 4 and 5, the variation of thermal properties affects the time temperature curves of steel members so constant values or approximate equations are adequate for the calculations likely to be performed by the users of NZS 3404. The approximate values most often recommended to use are those included in ENV 1993-1-2.

The limiting temperature of steel is a direct rearrangement of the formula to calculate the variation of yield strength with temperature. Depending on the form that the yield strength equation is will depend on the recommended limiting temperature equation. If the mechanical properties as recommended by EC3 are adopted by SNZ in the future, then it is subsequently recommended that the limiting temperature is similarly changed to that in the Eurocode. If a modification of the present formula, or a different equation modelling the variation of yield strength with temperature is then the limiting temperature of steel members should be changed accordingly.

7.2.6 External Steelwork:

Eurocode 3 has a large Annex that details the methods of heat transfer to external steelwork. The compartment is assumed to be confined to one storey and external openings are considered rectangular.

This Annex makes a distinction between whether or not members are engulfed in flame, depending on their locations relative to the openings from the fire compartment. It states that a member that is not engulfed in flame is assumed to receive radiative heat transfer from the openings that the member can 'see' and from the flames projecting from the openings. A member that is engulfed in flame is assumed to receive convective heat transfer as well as radiation from the engulfing flames and from the fire compartment openings from which the engulfing flame projects. Other openings and extruding flames may be neglected.

Member not engulfed in flame:

The average temperature of a steel member, T_m, not engulfed by flame can be determined by solving the following heat balance:

$$\sigma T_m^4 + \alpha T_m^4 = \Sigma I_z + \Sigma I_f + 293\alpha \qquad 7.13$$

where σ is the Stefan-Boltaman constant (5.67 x 10^{-12} W/m^{2}K^4)

α is the convective heat transfer coefficient (kW/m^{2}K)

I_z is the radiative heat flux from a flame (kW/m^2)

I_f is the radiative heat flux from an opening (kW/m^2)

Member engulfed in flame:

The average temperature of a steel member, T_m, that is engulfed in flame should be determined from the following equation:

$$\sigma T_m^4 + \alpha T_m^4 = I_z + I_f + \alpha T_z \qquad 7.14$$

where T_z is the flame temperature (K)

The radiative heat flux from an opening is to be determined from

$$I_f = \phi_f \varepsilon_f (1 - a_z) \sigma T_f^4 \qquad 7.15$$

where ϕ_f is the overall configuration factor of the member for radiative heat transfer from that opening

ε_f is the emissivity of the flames

a_z is the absorptivity of the flames

T_f is the temperature of the fire (K)

Eurocode has a large annex with guidelines establishing the methods of designing external steel members with regard to a fire compartment adjacent to the members as covered in Section 7.2.6. The British Steel Code BS 5850:Part 8 also has provisions for external steel work. It is recommended therefore that provisions are included giving guidelines for the use of external steel, but is not really necessary for them to be as detailed as included in EC3. BS 5950 suggests referring to texts for more information on the methods to analyse the likely effects of internal flames on the external steel members, but a simple method as listed in Section 7.2.6 should be adequate.

8 CONCLUSIONS AND RECOMMENDATIONS:

8.1 UNPROTECTED STEEL MEMBERS:

The temperature of unprotected steel members with time can be estimated using a variety of methods as shown in Section 4. The results of this section show that:

1. The equations recommended by ECCS (1985) provide a better time-temperature relationship that the equations found presently in NZS 3404;

2. The temperature limitations of the equations recommended by ECCS (1985) can be extended to 800 °C, and linear interpolation applied for temperatures below 400 °C to increase the use of these equations;

3. The lumped mass time step methods give accurate results when the calculated temperatures are compared to finite element computer models;

4. When evaluating the behaviour of a member exposed to fire on three sides, the maximum temperature in the web and lower flange is the same as with four sided protection

8.2 PROTECTED STEEL MEMBERS:

The results of analyses of protected steel members in Section 5 show that:

1. The ECCS (1985) equations give a good estimation of the time temperature relationship for protected steel when compared to the spreadsheet method and SAFIR.

2. The temperature limitations of the equations recommended by ECCS (1985) can be extended to 800 °C, and linear interpolation used for temperatures below 400 °C.

3. The lumped mass time step method gives temperatures that are close to those found from SAFIR simulations.

8.3 CHANGES TO NZS 3404:

The following recommendations are suggested for NZS 3404, based on the results found in this report:

1. A provision for a general calculation method of a structure using advanced calculation techniques such as finite element computer programmes;

2. Guidelines for designing steel members to have adequate strength when exposed to elevated temperatures;

3. The replacement of the approximate empirical equations with a lumped mass time step method for protected and unprotected steel;

4. The addition of the thermal properties of steel to the New Zealand Steel Code for use in the lumped mass time step equations;

5. An alteration to the mechanical properties of steel in the New Zealand Steel Code to provide consistency at higher temperatures;

6. The inclusion of provisions for the design of external steel members, or reference to this information to provide for circumstances external beams and columns may be subjected to a severe fire.

8.4 FURTHER RESEARCH:

This research report deals only with simply supported steel members. This work could be extended to cover more complicated steel structures with end conditions that are built in or continuous so that moment redistribution becomes a factor in the strength loss of steel and the strength of the structure will not be as reliant on the temperature of individual members. This would require more simulations in finite element computer packages of more complex arrangements than used in this report.

9 NOMENCLATURE:

When equations are taken from other sources, the notation listed below has been adopted to provide consistency throughout this report.

α	convective heat transfer coefficient (kW/m^2K)
χ_{fi}	reduction factor for flexural buckling in fire design situations
ε	Emissivity
γ_{GA}	partial factor for permanent actions in accidental design situations
η_{fi}	reduction factor for the design load level
φ	configuration factor
κ_1	adaptation factor for non-uniform temperatures across the cross section
κ_2	adaptation factor for non-uniform temperatures along the beam.
λ_{nt}	non dimensinal slenderness at normal temperatures
$\lambda_{nf,,t}$	non dimensinal slenderness at elevated temperatures
ρ_i	density of the insulation (kg/m^3)
ρ_s	density of the steel (kg/m^3)
σ	Stefan-Boltzmann constant (5.67×10^{-8} kW/m^2K^4)
$\psi_{1,1}$	combination factor for frequent values.
A	cross-sectional area of the steel (m^2)
A_v	area of the ventilation openings (m^2)
A_t	total internal surface area of the room (m^2)
c_i	specific heat of the insulation (J/kg K)
c_s	specific heat of the steel (J/kg K)
e_t	fuel load (MJ/m^2)
E_d	design effect of actions for normal temperatures (kN, kN.m)
$E_{fi,d}$	design effect of actions for the fire situation (kN, kN.m)
H_p/A	Section Factor (m^{-1})
F_v	opening factor = $A_v\sqrt{H_v}/A_t$
f_y	yield stress (MPa)
H_p	heated perimeter of steel (m)
h_c	convective heat transfer coefficient (W/m^2K)
h_t	total heat transfer coefficient (W/m^2K)
h_r	radiative heat transfer coefficient (W/m^2K)

H_v	height of the ventilation (m)
I_z	radiative heat flux from a flame (kW/m^2)
I_f	radiative heat flux from an opening (kW/m^2)
$k_o - k_6$	=regression coefficients
$k_{E,T}$	reduction factor for yield strength at elevated temperatures.
k_i	thermal conductivity of the insulation (W/m K)
k_s	thermal conductivity of the steel (W/m K)
$k_{y,T}$	reduction factor for yield strength at elevated temperatures.
M_f	design resistance of bending elements at elevated temperatures (kN.m)
$N_{b,fi}$	Design buckling resistance at elevated temperatures (kN)
N_f	Axial load capacity in fire situations (kN)
$Q_{k,1}$	principal variable load
$R_{fi,d,t}$	design resistance at elevated temperatures (kN, kN.m)
S	plastic section modulus (mm^3)
SF	Section factor, or H_p/A, (m^{-1})
t^*	fictitious time (h)
t''	real time (h)
T	temperature (°C or K)
T_0	initial temperature (°C or K)
T_f	temperature of the fire (°C or K)
T_s	temperature of the steel (°C or K)
T_l	limiting temperature (°C or K)
V_f	design shear resistance for elevated temperatures (kN)
V_s	design shear resistance for normal temperatures (kN)

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Appendix A – Spreadsheet Method:

Below is an example of a spreadsheet for an unprotected steel beam of size 530UB82.0 exposed to four sided exposure, as explained in Section 2.1.2.

F/V 178 m^{-1}

Time	Steel temperature	Fire temperature	Tf-Ts	Temp of steel (K)	Temp of fire(K)	Heat Transfer Co-eff	Diff in Steel Temp
0.0	20.0	20.0	0.0	293.0	293.0	#DIV/0!	0.0
1.0	20.0	261.1	241.1	293.0	534.1	34.7	19.0
2.0	39.0	404.3	365.3	312.0	677.3	42.5	35.2
3.0	74.2	476.2	402.0	347.2	749.2	48.7	44.4
4.0	118.6	524.5	405.9	391.6	797.5	54.8	50.4
5.0	169.0	561.0	392.0	442.0	834.0	61.1	54.3
6.0	223.4	590.4	367.0	496.4	863.4	67.8	56.4
7.0	279.8	614.9	335.1	552.8	887.9	75.0	57.0
8.0	336.8	635.9	299.1	609.8	908.9	82.8	56.1
9.0	393.0	654.4	261.5	666.0	927.4	91.0	53.9
10.0	446.9	670.8	224.0	719.9	943.8	99.4	50.5
11.0	497.4	685.6	188.3	770.4	958.6	108.0	46.1
12.0	543.5	699.1	155.6	816.5	972.1	116.5	41.1
13.0	584.6	711.5	126.9	857.6	984.5	124.7	35.9
14.0	620.5	722.9	102.4	893.5	995.9	132.4	30.7
15.0	651.2	733.5	82.3	924.2	1006.5	139.5	26.0
16.0	677.3	743.4	66.2	950.3	1016.4	145.9	21.9
17.0	699.2	752.7	53.6	972.2	1025.7	151.7	18.4
18.0	717.6	761.5	43.9	990.6	1034.5	156.9	15.6
19.0	733.2	769.7	36.5	1006.2	1042.7	161.6	13.4
20.0	746.6	777.6	31.0	1019.6	1050.6	165.9	11.7
21.0	758.3	785.0	26.8	1031.3	1058.0	169.8	10.3
22.0	768.6	792.1	23.6	1041.6	1065.1	173.5	9.3
23.0	777.8	798.9	21.1	1050.8	1071.9	176.9	8.4
24.0	786.3	805.4	19.1	1059.3	1078.4	180.1	7.8
25.0	794.1	811.6	17.5	1067.1	1084.6	183.2	7.3
26.0	801.4	817.6	16.2	1074.4	1090.6	186.1	6.8
27.0	808.2	823.3	15.1	1081.2	1096.3	188.9	6.5
28.0	814.7	828.8	14.2	1087.7	1101.8	191.6	6.2
29.0	820.8	834.1	13.3	1093.8	1107.1	194.3	5.9
30.0	826.7	839.3	12.6	1099.7	1112.3	196.8	5.6

Figure A.1: Example of the spreadsheet method for an unprotected beam.

Below is an example of a spreadsheet for a protected steel beam of size 530UB82.0 exposed to four sided exposure, as explained in Section 2.1.3.

k_i	0.19	W/m K
d_i	0.02	m
ρ_i	775	kg/m^3
c_i	1100	J/kg K

ρ_s	7850	kg/m^3
c_s	600	J/kg K
H_p/A	178	m^{-1}

Time	Steel temperature	Fire temperature	Tf-Ts	Temp of steel (K)	Temp of fire(K)	Diff in Steel Temp
0.0	20.0	20.0	0.0	293.0	293.0	0.0
1.0	20.0	261.1	241.1	293.0	534.1	3.9288
2.0	23.9	404.3	380.4	296.9	677.3	6.1973
3.0	30.1	476.2	446.0	303.1	749.2	7.2670
4.0	37.4	524.5	487.1	310.4	797.5	7.9366
5.0	45.3	561.0	515.7	318.3	834.0	8.4020
6.0	53.7	590.4	536.6	326.7	863.4	8.7429
7.0	62.5	614.9	552.4	335.5	887.9	8.9999
8.0	71.5	635.9	564.5	344.5	908.9	9.1965
9.0	80.7	654.4	573.7	353.7	927.4	9.3475
10.0	90.0	670.8	580.8	363.0	943.8	9.4630
11.0	99.5	685.6	586.2	372.5	958.6	9.5501
12.0	109.0	699.1	590.1	382.0	972.1	9.6141
13.0	118.6	711.5	592.8	391.6	984.5	9.6589
14.0	128.3	722.9	594.6	401.3	995.9	9.6876
15.0	138.0	733.5	595.5	411.0	1006.5	9.7026
16.0	147.7	743.4	595.7	420.7	1016.4	9.7060
17.0	157.4	752.7	595.3	430.4	1025.7	9.6993
18.0	167.1	761.5	594.4	440.1	1034.5	9.6839
19.0	176.8	769.7	593.0	449.8	1042.7	9.6608
20.0	186.4	777.6	591.1	459.4	1050.6	9.6311
21.0	196.1	785.0	589.0	469.1	1058.0	9.5955
22.0	205.7	792.1	586.5	478.7	1065.1	9.5547
23.0	215.2	798.9	583.7	488.2	1071.9	9.5094
24.0	224.7	805.4	580.6	497.7	1078.4	9.4601
25.0	234.2	811.6	577.4	507.2	1084.6	9.4071
26.0	243.6	817.6	574.0	516.6	1090.6	9.3511
27.0	253.0	823.3	570.3	526.0	1096.3	9.2922
28.0	262.2	828.8	566.6	535.2	1101.8	9.2308
29.0	271.5	834.1	562.7	544.5	1107.1	9.1672
30.0	280.6	839.3	558.6	553.6	1112.3	9.1016

Figure A.2: Example of the spreadsheet method for a protected beam.

APPENDIX B – SAFIR:

In Figure B.2 is the windows view of the pre-processor developed by Mason, 2000, with the functions used for this report.

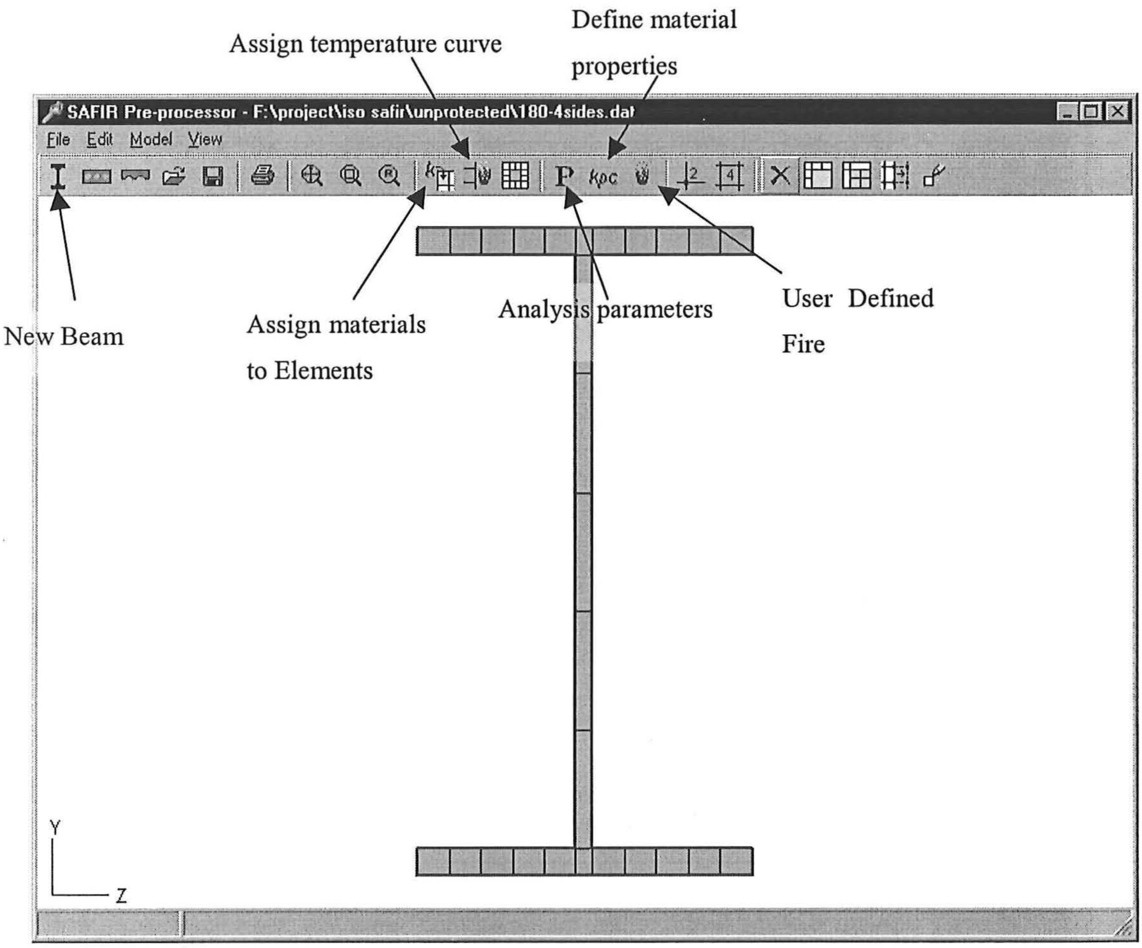

Figure B.1: Window developed by John Mason as a preprocessor for the SAFIR programme.

SAFIR INPUT

*.dat file developed by the pre processor shown in Figure B.1 for a 180UB16.1 beam exposed to fire on four sides.

```
    NPTTOT         2
     NNODE    56
      NDIM     2
NDIMMATER      1
  NDDLMAX      1
      FROM     1    TO    56 STEP    1 NDDL    1

  TEMPERAT
      TETA      0.90
  TINITIAL        20
  MAKE.TEM
LARGEUR11      10000
LARGEUR12       1000
  NORENUM
180-4sides.str
180-4sides.tem
PRECISION      0.001
      TIME
                  10        300
                  20        600
                  30       3600
   ENDTIME
IMPRESSION
TIMEPRINT         30
```

*.str file developed by the pre processor in Figure B.1 for a 180UB16.1 beam exposed to an ISO 834 fire on 4 sides.

```
NMAT     1

  ELEMENTS

     SOLID   27

        NG    2

     NVOID    0


     NODES

      NODE    1          0         0

      NODE    2          0    0.0085

      NODE    3          0    0.0171

      NODE    4          0    0.0256

      NODE    5          0    0.0342
      NODE    6          0    0.0427
      NODE    7          0    0.0472
      NODE    8          0    0.0558
      NODE    9          0    0.0643
      NODE   10          0    0.0729
      NODE   11          0    0.0814
      NODE   12          0      0.09
      NODE   13      0.007         0
      NODE   14      0.007    0.0085
      NODE   15      0.007    0.0171
      NODE   16      0.007    0.0256
      NODE   17      0.007    0.0342
      NODE   18      0.007    0.0427
      NODE   19      0.007    0.0472
      NODE   20      0.007    0.0558
      NODE   21      0.007    0.0643
      NODE   22      0.007    0.0729
      NODE   23      0.007    0.0814
      NODE   24      0.007      0.09
      NODE   25     0.0388    0.0427
      NODE   26     0.0388    0.0472
      NODE   27     0.0706    0.0427
      NODE   28     0.0706    0.0472
      NODE   29     0.1024    0.0427
      NODE   30     0.1024    0.0472
      NODE   31     0.1342    0.0427
      NODE   32     0.1342    0.0472
      NODE   33      0.166         0
      NODE   34      0.166    0.0085
      NODE   35      0.166    0.0171
      NODE   36      0.166    0.0256
      NODE   37      0.166    0.0342
      NODE   38      0.166    0.0427
```

```
      NODE   39      0.166     0.0472
      NODE   40      0.166     0.0558
      NODE   41      0.166     0.0643
      NODE   42      0.166     0.0729
      NODE   43      0.166     0.0814
      NODE   44      0.166       0.09
      NODE   45      0.173          0
      NODE   46      0.173     0.0085
      NODE   47      0.173     0.0171
      NODE   48      0.173     0.0256
      NODE   49      0.173     0.0342
      NODE   50      0.173     0.0427
      NODE   51      0.173     0.0472
      NODE   52      0.173     0.0558
      NODE   53      0.173     0.0643
      NODE   54      0.173     0.0729
      NODE   55      0.173     0.0814
      NODE   56      0.173       0.09
  NODELINE             0.0        0.0
     YC ZC             0.0        0.0
 FIXATIONS

NODOFSOLID
      ELEM    1    1    2   14   13    1
      ELEM    2    2    3   15   14    1
      ELEM    3    3    4   16   15    1
      ELEM    4    4    5   17   16    1
      ELEM    5    5    6   18   17    1
      ELEM    6    6    7   19   18    1
      ELEM    7    7    8   20   19    1
      ELEM    8    8    9   21   20    1
      ELEM    9    9   10   22   21    1
      ELEM   10   10   11   23   22    1
      ELEM   11   11   12   24   23    1
      ELEM   12   18   19   26   25    1
      ELEM   13   25   26   28   27    1
      ELEM   14   27   28   30   29    1
      ELEM   15   29   30   32   31    1
      ELEM   16   31   32   39   38    1
      ELEM   17   33   34   46   45    1
      ELEM   18   34   35   47   46    1
      ELEM   19   35   36   48   47    1
      ELEM   20   36   37   49   48    1
      ELEM   21   37   38   50   49    1
      ELEM   22   38   39   51   50    1
      ELEM   23   39   40   52   51    1
      ELEM   24   40   41   53   52    1
      ELEM   25   41   42   54   53    1
      ELEM   26   42   43   55   54    1
      ELEM   27   43   44   56   55    1
  FRONTIER
    1     FISO                FISO      FISO
    2     FISO                FISO
    3     FISO                FISO
    4     FISO                FISO
    5     FISO                FISO
    6     FISO
    7     FISO                FISO
    8     FISO                FISO
    9     FISO                FISO
   10     FISO                FISO
```

```
     11       FISO      FISO      FISO
     12                 FISO                FISO
     13                 FISO                FISO
     14                 FISO                FISO
     15                 FISO                FISO
     16                 FISO                FISO
     17       FISO                FISO      FISO
     18       FISO                FISO
     19       FISO                FISO
     20       FISO                FISO
     21       FISO                FISO
     22                           FISO
     23       FISO                FISO
     24       FISO                FISO
     25       FISO                FISO
     26       FISO                FISO
     27       FISO      FISO      FISO

  SYMMETRY
    ENDSYM
 MATERIALS
  STEELEC2
                                                     25
9        0.5
```

DIAMOND OUTPUT

From the Diamond output programme, this is the temperature layout showing the temperature of the different elements at a chosen time:

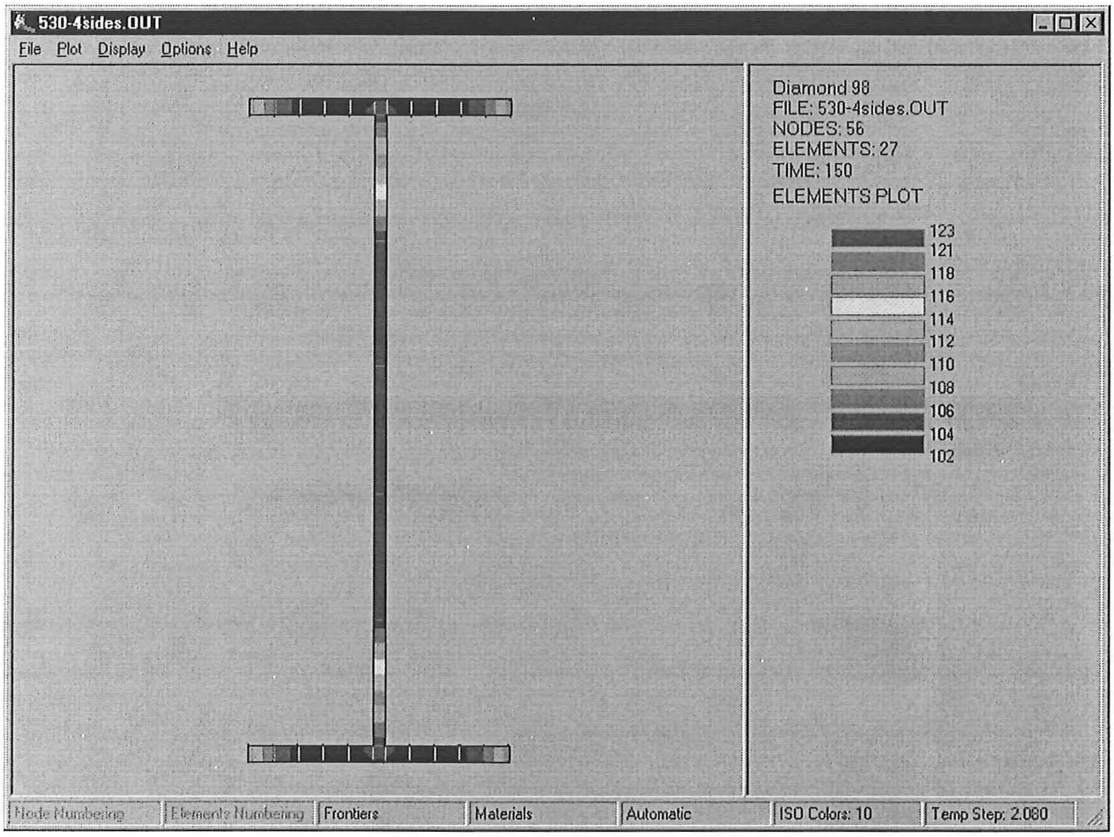

Figure B.2: Output window of the Diamond programme.

APPENDIX C – FIRECALC

Below in Figure C.1 is the DOS format for the Firecalc programme, Item 11 for steel beam load bearing capacity calculations:

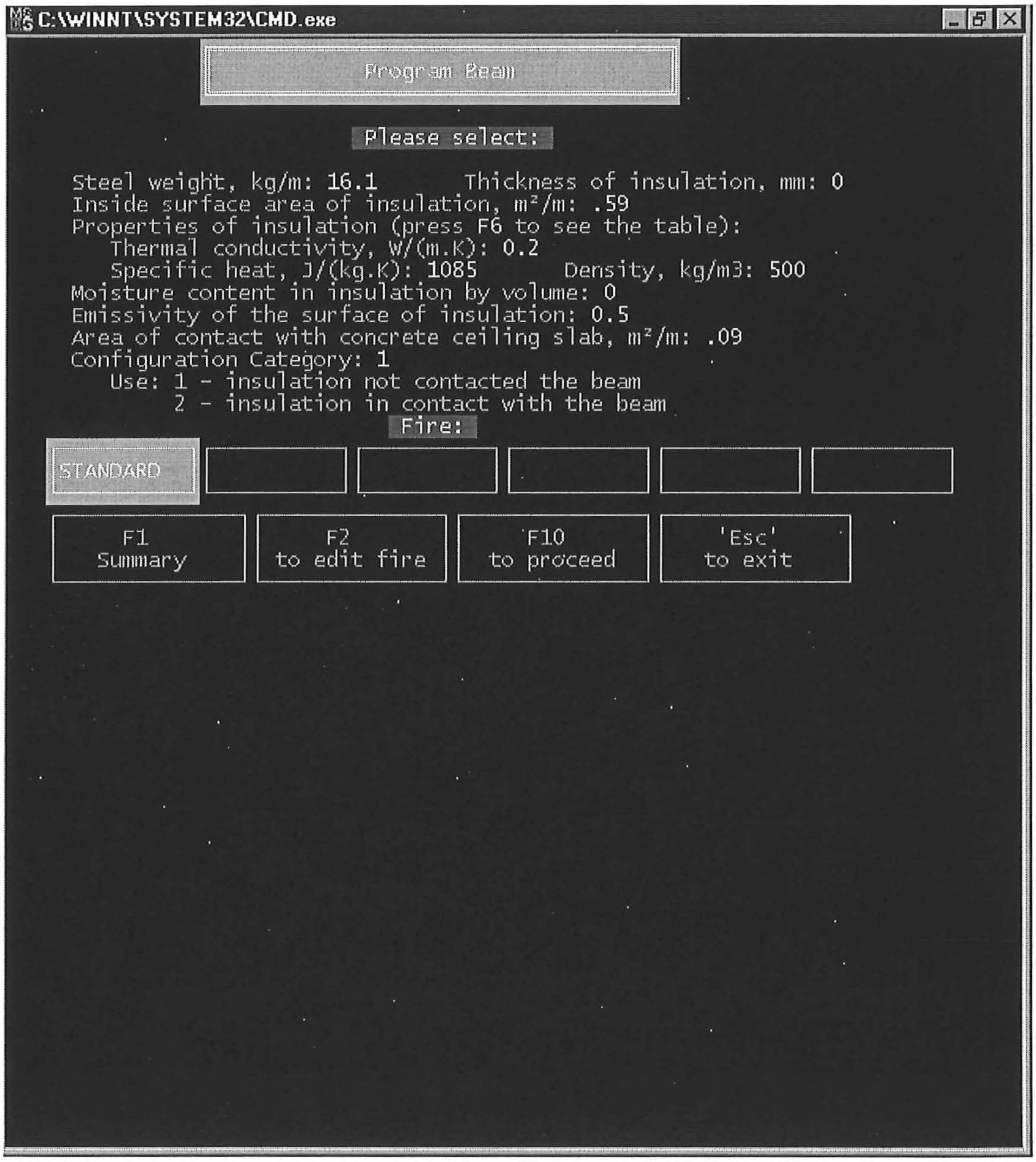

Figure C.1: Window format for Firecalc.

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